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Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture

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[1] Dr. Sohngen was on sabbatical from The Ohio State University when working on this report at RTI.

[2] Dr. Gillig was at Texas A&M University when she performed this work.

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Executive Summary

Forestry and agricultural activities are widely recognized as potential greenhouse gas (GHG) mitigation options. Activities in forestry and agriculture can reduce and avoid the atmospheric buildup of the three most prevalent GHGs directly emitted by human actions: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The removal of atmospheric CO_2 through sequestration in carbon "sinks" is a mitigation option in forestry and agriculture that has received particular attention.

Currently in the United States, forest and agricultural lands comprise a net carbon sink of almost 830 teragrams (Tg or million tonnes[1]) of CO_2 equivalent (or nearly 225 Tg of carbon equivalent) per year, according to the U.S. GHG inventory (EPA 2005). Removal of atmospheric CO_2 through carbon sequestration is greater than CO_2 emissions from events such as forest harvests, land conversion to other uses, or fire. The U.S. net carbon sink—over 90 percent of which occurs on forest lands—currently offsets 12 percent of U.S. GHG emissions from all sectors of the economy on an annual basis (EPA 2005). The agriculture sector, however, is a net emitter of GHGs. Agricultural CH_4 and N_2O emissions are responsible for over 6 percent of all annual U.S. GHG emissions (EPA 2005). After accounting for both carbon sequestration and non-CO_2 emissions, the forest and agriculture sectors comprise a net GHG sink that offsets almost 6 percent of total U.S. GHG emissions.

This report evaluates the potential for additional carbon sequestration and GHG reductions in U.S. forestry and agriculture over the next several decades and beyond. It reports these reductions as changes from baseline trends, starting in 2010 and projected out 100 years to 2110. The report employs the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG). FASOMGHG is a partial equilibrium economic model of the U.S. forest and agriculture sectors, with land use competition between them, and linkages to international trade. FASOMGHG includes most major GHG mitigation options in U.S. forestry and agriculture; accounts for changes in CO_2, CH_4, and N_2O from most activities; and tracks carbon sequestration and carbon losses over time. It also projects a dynamic baseline and reports all additional GHG mitigation as changes from that baseline. FASOMGHG tracks five forest product categories and over 2,000 production possibilities for field crops, livestock, and biofuels for private lands in the conterminous United States broken into 11 regions. Public lands are not included.

FASOMGHG evaluates the joint economic and biophysical effects of a range of GHG mitigation scenarios, under which costs, mitigation levels, eligible activities, and GHG coverage may vary. The six scenarios evaluated in this report are constant GHG prices, rising GHG prices, fixed national mitigation levels, inclusion of selected mitigation activities only, incentive payments for

[1] A tonne is a metric ton, which equals one megagram (Mg). 1 tonne CO_2 = 0.27 tonnes of carbon. 1 tonne of carbon = 3.67 tonnes of CO_2.

CO_2 only, and payments on a per-acre versus per-tonne basis. GHG mitigation incentives are estimated by dollars per tonne of CO_2 equivalent (\$/t CO_2 Eq.) payments for four of the six scenarios above. The model and analysis cover the 100 years from 2010 to 2110, but three focus dates are highlighted: 2015, 2025, and 2055. FASOMGHG's standard GHG accounting and payment approach is a comprehensive, pay-as-you-go system, for all applicable GHGs and activities over time.

The analysis reported here is unique from other studies conducted on forestry and agricultural mitigation options on a number of fronts. First, the range of covered activities across the sectors is wide. Most comparable studies look at just one of the sectors or at one or a small subset of activities within each sector, while this report examines a fairly comprehensive set of activities across the two sectors covering a vast majority of all GHG effects. Of particular note are the inclusions of biofuels and non-CO_2 mitigation options in agriculture. Second, the intertemporal dynamics of the economic and biophysical systems within FASOMGHG allow for an accounting of mitigation over time and by region, and for quantification of leakage effects that other studies generally have not produced. And third, the inclusion of non-GHG co-effects allows insights into the multiple environmental and economic tradeoffs that pertain to GHG mitigation in these sectors.

Highlights of the analysis include the following:

GHG reduction incentives can generate substantial mitigation from the U.S. forest and agriculture sectors especially in the first few decades. Total national mitigation annually is estimated to average almost 630 Tg CO_2/yr (170 Tg C) in the first decade and 655 Tg CO_2/yr (180 Tg C) by 2025, under one of the moderate GHG prices considered (\$15 t/CO_2 Eq, or \$55/t C, remaining constant over time). Mitigation then declines to about 85 Tg CO_2/yr (23 Tg C) by 2055. The rate of annual mitigation (i.e., occurring in a given year) declines over time, as the result of saturating carbon sequestration (to a new equilibrium) in forestry and agriculture and carbon losses after timber harvesting. Cumulative GHG mitigation (i.e., achieved in the years up to a given year), however, steadily increases for constant price scenarios.

If GHG prices rise over time, however, GHG mitigation is shown to start low and increase over time. Farmers and foresters who want to optimize their returns from any GHG payments are assumed to know that GHG prices will rise in future decades and may delay mitigation practices until prices rise. The mitigation timing results, however, are sensitive to the FASOMGHG model's assumptions about landowner knowledge of future price behavior, known as perfect foresight.

The optimal portfolio and timing of mitigation strategies are affected by the GHG price levels. At relatively low GHG prices (≤\$5/t CO_2 Eq.) and in early years, carbon sequestration in agricultural soils and carbon sequestration in forest management (i.e., harvest and regrowth practices) are the dominant mitigation strategies. Afforestation becomes the leading strategy at middle to higher prices (≥\$15/t CO_2 Eq.) in the early to middle years to 2050, but both afforestation and sequestration in agricultural soils get reversed by 2055, because of carbon saturation, harvesting, and practice reversion. Biofuels dominate the portfolio at the highest prices (\$30 and \$50/t CO_2 Eq.) and in later years beyond 2050.

Agricultural CH_4 and N_2O mitigation is a relatively small but steady part of the mitigation portfolio. Biofuels and agricultural CH_4 and N_2O mitigation are permanent emissions reductions (i.e., they do not face the risk of GHG benefit reversal).

Mitigation potential is likely to have a regional, uneven distribution. The South-Central, Corn Belt, and Southeast regions possess the largest competitive potential to generate GHG mitigation, while the Rockies, Southwest, and Pacific Coast regions generate the least mitigation. Forest management in the South-Central region generates the most GHG mitigation, followed by agricultural soil carbon seques¬tration in the Corn Belt, Lake

States, and Plains, in low, constant price scenarios. Afforestation in the South-Central and Corn Belt regions is dominant at higher price scenarios. Biofuels become a significant part of the mitigation portfolio at high prices and occur primarily in the Northeast, Southeast, and South-Central regions.

If a national GHG mitigation quantity in a given year is an objective, but economic incentives do not continue after that date, then carbon sequestered in previous decades is likely to be reversed. Landowners return to other, more economically attractive land management choices when GHG incentives disappear.

Leakage of GHG benefits from management activities in one region to other regions may be significant in scenarios where only selected activities (e.g., afforestation) are eligible for inclusion in a mitigation scheme. This leakage may vary by activity, by region, and over time. Agricultural activities, including soil carbon sequestration, appear to have minimal leakage, however (less than 6 percent).

Large changes in land use and production due to mitigation activities can have substantial non-GHG environmental co-effects. Even a low GHG price (e.g., $5/tonne) can induce changes in tillage practices and promote agricultural soil carbon sequestration at a significant scale. Tillage practice changes also reduce erosion and nutrient run-off into waterways as a co-benefit, but can lead to a modest increase in pesticide use as a co-cost. Taking environmental co-effects into consideration could affect the relative attractiveness of competing mitigation options. In general, the more aggressive the mitigation action, the more likely that co-effects may factor into the net benefits of GHG mitigation.

Several key issues related to the design of an incentive system can affect the magnitude, timing, and duration of GHG benefits and cost. These issues include if, and how, baseline setting, leakage of GHG benefits, and the risk of reversal of carbon management mitigation are addressed. Another key issue is how mitigation is quantified and reported. Use of cumulative mitigation (i.e., total mitigation to some future date) rather than annual mitigation (i.e., in a given year) may more accurately summarize the net GHG contribution of forest or soil carbon management activities that face some risk of reversal. Other considerations include which activities are eligible for inclusion, payment options (per acre versus per tonne), and the potential adjustment of mitigation benefits to account for reversal risk, leakage, and baseline additionality.

CHAPTER 1

Introduction

Forestry and agricultural activities are widely recognized as potential greenhouse gas (GHG) mitigation options. Activities in forestry and agriculture can reduce and avoid the atmospheric buildup of the three most prevalent GHGs directly emitted by human actions: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 is the gaseous form of carbon bound with oxygen atoms.

The removal of atmospheric CO_2 through sequestration in carbon "sinks" is a mitigation option in forestry and agriculture that has received particular attention. Sequestration is the process of increasing the carbon content of a carbon pool other than the atmosphere (IPCC 2000). Terrestrial carbon pools include tree biomass (roughly 50 percent carbon), soils, and wood products. A carbon pool is a net sink if, over a certain time interval, more carbon is flowing into the pool than is flowing out of the pool. Likewise, a carbon pool can be a net source of CO_2 emissions if less carbon is flowing into the pool than is flowing out of the pool (IPCC 2000).

The forest and agriculture sectors can therefore act as either sources or sinks of CO_2 emissions. Agriculture (including croplands and livestock) is a particularly large source of CH_4 and N_2O emissions. Globally, land-use change, primarily tropical deforestation, accounts for approximately 20 percent of the world's annual, anthropogenic CO_2 emissions (IPCC 2000). An even greater amount of atmospheric CO_2 is removed by forests than is emitted by land-use change, such that the net global terrestrial sink (sink minus source) offsets approximately 11 percent of the world's CO_2 emissions due to fossil fuel combustion (IPCC 2000). Meanwhile, agriculture accounts for approximately 50 percent of global anthropogenic CH_4 emissions and 85 percent of global N_2O emissions (Scheehle and Kruger in press). CH_4 and N_2O are relatively potent greenhouse gases and can be placed on a comparable climatic basis with CO_2 through a Global Warming Potential (GWP) factor (see Box 1-1).

Box 1-1: Relative Global Warming Potential of Non-CO_2 Gases

The Global Warming Potential (GWP) compares the relative ability of each GHG to trap heat in the atmosphere over a certain time frame. Per IPCC (1996) guidelines, CO_2 is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH_4 is 21, implying that a ton of methane is 21 times more potent than a ton of CO_2. The GWP for N_2O is 310. These values can be further transformed from CO_2 to carbon equivalent by dividing by 3.67, the mass ratio of CO_2 to C.

Note that GWPs from the *IPCC Third Assessment Report* (2001) are not used in this report because international GHG reporting guidelines are still based on the 1996 *IPCC Second Assessment Report*.

In the United States, forest and agricultural lands also comprise a net carbon sink. Removal of atmospheric CO_2 through sequestration is greater than CO_2 emissions through events such as forest harvests, land conversions or other uses, or fire. The U.S. carbon sink—over 90 percent of which occurs on forest lands—currently offsets 12 percent of U.S. GHG emissions from all sectors of the economy (EPA 2005; Figure 1-1). Agriculture accounts for about 30 percent of all CH_4 emissions and 72 percent of all N_2O emissions in the United States (op cit). Taken together, agricultural CH_4 and N_2O emissions are responsible for about 6 percent of all U.S. GHG emissions, expressed on a GWP-weighted CO_2 equivalent basis (op cit).

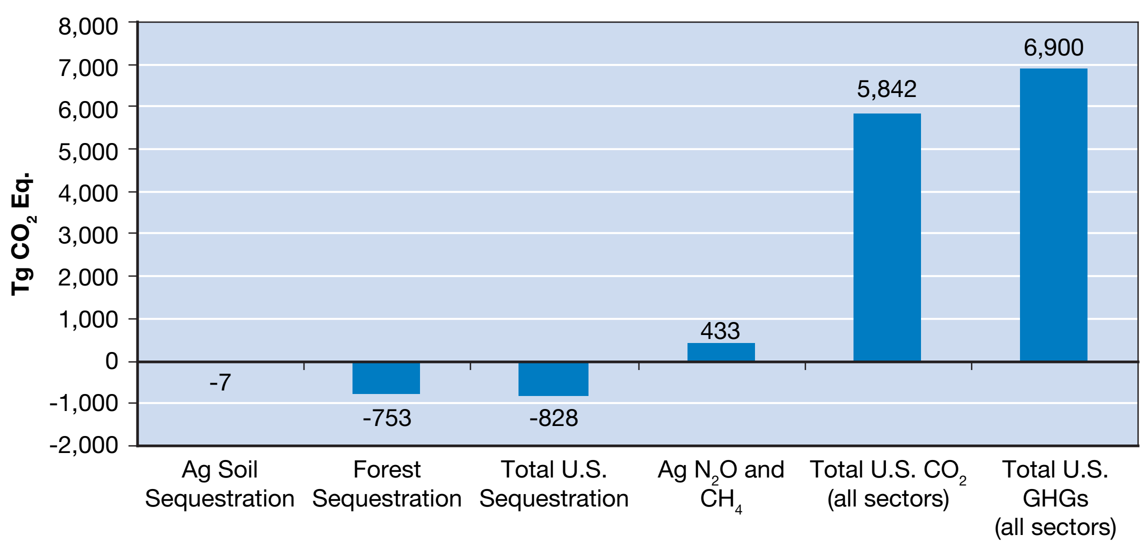
Key individual GHG mitigation options in U.S. forestry and agriculture include

- afforestation (tree planting);
- forest management, including silviculture, harvests, and forest preservation;
- agricultural soil carbon sequestration (primarily through changes in cropland tillage practices);
- fossil fuel use reduction associated with altered practices in agriculture;
- agricultural CH_4 and N_2O emission reduction (through a variety of modifications to livestock management and fertilizer applications); and
- biofuel offsets of fossil fuels (derived from bioenergy crops such as switchgrass).

These options generally fall into three categories (see IPCC [2001, 2000]): 1) options that avoid CO_2 emissions by preserving existing pools or sinks of carbon in tree biomass and soils (e.g., forest preservation), 2) options that enhance the removal of atmospheric CO_2 (sinks) through sequestration (e.g., afforestation), and 3) options that directly reduce fossil fuel-related CO_2 or CH_4 and N_2O emissions (e.g., biofuels and reduced fertilizer use). Chapter 2 discusses the individual mitigation options in greater detail.

Forestry and agricultural activities that either preserve or enhance carbon sinks exhibit unique and important features compared to mitigation options that directly reduce fossil fuel-related CO_2 or CH_4 and N_2O emissions. Two distinguishing characteristics are the saturation over time of carbon sequestration in vegetative biomass and soils, as a new equilibrium is reached for a given level of inputs, and the potential reversibility, or re-release, back to the atmosphere of sequestered carbon through natural or anthropogenic disturbances (e.g., tillage, or fire). The reversibility of

Figure 1 1: Forestry and Agriculture Net Contribution to GHG Emissions in the United States, 2003[a]



[a] Total agriculture and forestry sequestration also includes urban trees and landfilled yard trimmings and food scraps. Negative values represent a sink, positive values a source.

Source: EPA (2005).

carbon sequestration benefits is often referred to as the duration or permanence issue. Analyses presented in the report highlight the implications of saturation and reversibility of carbon sequestration in forestry and agriculture.

Purpose and Approach of this Report

This report aims to assess the GHG mitigation potential from forestry and agriculture in the United States over the next several decades, out to the 2050s, and in some cases beyond.

More specifically, the report aims to examine the following questions:

- What is the total GHG mitigation potential of the full suite of forestry and agricultural activities over time and at different costs?
- How does the portfolio of forestry and agricultural activities change over time and at different levels of GHG reduction incentives (or "GHG prices")?
- What is the regional distribution of GHG mitigation opportunities within the United States?
- How does the portfolio of activities, time profile, and regional distribution change across scenarios that reflect constant prices for GHG mitigation, rising prices, and fixed mitigation levels?
- What are the implications of carbon saturation and reversibility (or duration)?
- How do leakage and other implementation issues affect GHG mitigation benefits?
- What are some of the non-GHG environmental co-effects of GHG mitigation activities?
- What appear to be the top mitigation options, nationally and regionally, taking GHG, economic, implementation, and other environmental factors into account?

The analysis uses the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG) to examine these questions. FASOMGHG is a partial equilibrium economic model with comprehensive GHG accounting of the forest and agriculture sectors of the U.S. economy, linked to the rest of the world by international trade linkages. FASOMGHG can gauge the national aggregate response to GHG incentives (prices or GHG mitigation targets) and identify the most cost-effective mitigation opportunities at the national and regional levels. FASOMGHG can examine various scenarios with different approaches to achieving GHG mitigation (e.g., where all forestry and agricultural activities are included, where individual activities are included, or where all or individual GHGs are included).

All reported GHG mitigation activities in FASOMGHG occur as changes from a business-as-usual or baseline trajectory of carbon sequestration rates, GHG emissions, and economic activity in U.S. forestry and agriculture over time. Thus, *the mitigation results reported here are additional to projected baseline activity and GHG emission or sequestration levels*. FASOMGHG also reports some non-GHG environmental co-effects (such as changes in nonpoint loadings of nitrogen and phosphorous from agriculture) for a more complete analysis of mitigation outcomes.

Organization of Report

This report is organized as follows:

- **Chapter 2** describes the GHG mitigation options in U.S. forestry and agriculture represented in the FASOMGHG model, as well as some others not explicitly modeled for this report.
- **Chapter 3** presents the modeling framework of FASOMGHG and the model's projected baseline (with a brief comparison to other baseline studies), against which all mitigation estimates in subsequent chapters are reported.
- **Chapter 4** presents GHG mitigation results for the full suite of forestry and agricultural activities. Scenarios include a range of constant and rising GHG price incentives over time. Regional GHG mitigation results for these scenarios are presented as well.

- **Chapter 5** presents GHG mitigation results for the following selective scenarios: 1) three fixed GHG mitigation levels, 2) selection of individual or subsets of forestry and agricultural activities, and 3) addressing of CO_2 reductions only (versus all GHGs).
- **Chapter 6** evaluates some implications of taking activity-specific mitigation approaches and different payment methods. The chapter also presents estimates of the potential for "leakage," or the shifting of emissions to activities not subject to incentives.
- **Chapter 7** provides more detail on the non-GHG environmental co-effects of GHG mitigation activities.
- **Chapter 8** concludes the report by highlighting the report's key findings and the insights they hold for the realization of GHG mitigation potential in forestry and agriculture.

CHAPTER 2

Greenhouse Gas Mitigation Options in U.S. Forestry and Agriculture

Chapter 2 Summary

GHG mitigation opportunities in forestry and agriculture include afforestation (tree planting), forest management (e.g., altering harvest schedules or management inputs), forest preservation, agricultural soil tillage practices, grassland conversion, grazing management, riparian buffers, biofuel substitutes, fertilization management, and livestock and manure management. Each of these opportunities is described, with emphasis on their ability to avoid, sequester, and/or reduce CO_2, CH_4, and N_2O emissions. Sequestration activities can enhance and preserve carbon sinks and include afforestation, forest management, and agricultural soil tillage practices. Agricultural sources of CH_4, N_2O, and fossil fuel CO_2 can be reduced through changes in fertilizer applications and livestock and manure management. CO_2 emissions can be offset through biofuels, such as switchgrass and short-rotation tree species, which can be grown and used instead of fossil fuels to generate electricity.

This chapter also considers the unique time dynamics and accounting issues of carbon sequestration options: saturation (or equilibrium level) of carbon sequestration over time, potential reversibility of carbon benefits, and fate of carbon stored in products after forest harvests. In contrast, agricultural non-CO_2, fossil fuel CO_2, and biofuel options do not exhibit saturation or reversibility and are therefore generally considered permanent. Most mitigation opportunities described in this chapter are included in the analyses described in later chapters.

Forestry and agricultural activities can help reduce and avoid the atmospheric buildup of CO_2, CH_4, and N_2O in a number of ways. Atmospheric CO_2 can be removed and sequestered in tree biomass and soils, which can act as carbon sinks. Carbon stored in tree biomass and soils can be protected and preserved to avoid CO_2 releases to the atmosphere. Emissions of CO_2 can be avoided by reducing the use of energy-intensive inputs or by using biofuels, produced in the forest and agriculture sectors, instead of fossil fuels to produce energy. And agricultural CH_4 and N_2O emissions can be directly reduced by modifying livestock management and fertilizer applications. This chapter discusses the key forestry and agricultural mitigation options that either avoid, sequester, and/or reduce CO_2, CH_4, and N_2O. This chapter also discusses important issues related to the reversibility or permanence of forestry and agricultural options involving carbon sinks. The chapter presents the individual mitigation options as activities undertaken by landowners at the farm or forest-stand level. Subsequent chapters characterize the extent to which these mitigation options can be brought about by economic incentives operating at a nationally or regionally aggregated level. Examples of such incentives currently in place include government programs such as the Farm Bill, or voluntary GHG registries.

Carbon Sequestration

A number of practices within the forest and agriculture sectors can mitigate the atmospheric build-up of GHGs by removing CO_2 from the atmosphere and then storing it in forest and agro-ecosystems at a rate greater than its release back to the atmosphere through human and natural disturbances. These carbon sequestration activities can take on a variety of forms as discussed below.

Afforestation

Afforestation can be defined broadly as the establishment of trees on lands that were without trees for some period of time. Differing interpretations of this time period will dictate whether the establishment of forest cover is considered to represent afforestation or reforestation. The Intergovernmental Panel on Climate Change (IPCC) defines afforestation as the planting of new forests on lands that, historically, have not contained forests (IPCC 2000).

Reforestation often refers to the reestablishment of forest after a harvest in the United States. This report treats reforestation, or changes in the harvest–regeneration cycle, as part of "forest management," discussed below. FASOMGHG models afforestation separately, but reforestation is embedded within the broader activity of forest management in FASOMGHG and not treated separately.

Afforestation enhances carbon sequestration because land is allocated away from uses with relatively low carbon storage potential (e.g., conventional crop agriculture) to forest cover with higher carbon storage potential. Carbon accumulates in forest soils and biomass, the latter both below ground in the form of roots and above ground in stem, branches, and leaves. The rate of carbon accumulation for afforestation varies and depends on the newly planted tree species, climate, soil type, management, and other site-specific characteristics (e.g., 2.2 to 9.5 tonnes of CO_2 per acre per year, as reported by Birdsey [1996]; see Table 2-1). As a carbon sequestration activity, afforestation primarily affects atmospheric CO_2. The movement of land from agricultural use to forest also generally leads to a reduction in the various GHG emissions from agriculture, as described below. Most recent afforestation in the United States has occurred on pasturelands, where from 1982 to 1997 over 14 million acres were converted to forest cover (USDA NRCS 2000).

Forest Management

Forest management has traditionally focused on maximizing the value of harvested commercial timber over time. However, forests also can be managed to enhance carbon sequestration, via silvicultural practices or conservation of standing stocks. A managed forest will consist of one or several tree species in stands, and the mix can be designed so that the trees aid one another to ensure the fastest and most efficient biomass growth and thus higher sequestration potential. The landowner may choose to plant a moderately fast-growing species to accumulate timber (and carbon) faster; he or she may also use practices such as fertilization, controlled burning, and thinning to increase forest and carbon productivity.

Managed forests pass through multiple stand ages ranging from stand establishment to harvest. In a forest managed for timber production, the optimal harvest age is the time when the value of the additional timber growth obtained by delaying the harvest further is overtaken by the opportunity cost of the delay. Traditional forest rotation lengths vary by region and species type. The nonindustrial private forests (NIPF) of the southern United States are commonly managed with softwood or mixed species on a rotation of approximately 25 to 35 years or more. Rotations in commercial forestry, as practiced on forest industry-owned lands or very intensively managed NIPF lands, may be as short as half the length of the more typical NIPF rotation. The forest rotations of the western United States tend to be longer (between 45 and 60 years), because they consist of species that culminate growth at a later age. The varying rotation lengths allow for the production of multiple forest products including smaller-diameter pulpwood and larger-diameter sawtimber.

When carbon is considered a forest output, the value of delaying the rotation is higher because carbon accumulates as the trees grow (van Kooten, Binkley, and Delcourt 1995, Murray 2000). Thus, forest managers can enhance carbon sequestration

Table 2-1: Representative Carbon Sequestration Rates and Saturation Periods for Key Agriculture, Land-Use Change, and Forestry Practices

Activity	**Representative Carbon Sequestration Rate in U.S.** (Tonnes of CO_2 per acre per year, unless otherwise indicated)	**Time Over which Sequestration May Occur before Saturating** (Assuming no disturbance, harvest, or interruption of practice)	References
Afforestation[a]	2.2 – 9.5[b]	90 – 120+ years	Birdsey (1996)
Reforestation[c]	1.1 – 7.7[d]	90 – 120+ years	Birdsey (1996)
Avoided deforestation	83.7 – 172.1[e]	N.A.	U.S. Government (2000)
Changes in forest management	2.1 – 3.1[f]	If wood products included in accounting, saturation does not necessarily occur if carbon continuously flows into products	Row (1996)
Reduced tillage on croplands[g]	0.6 – 1.1	15 – 20 years	West and Post (2002)
	0.7[h]	25 – 50 years	Lal et al. (1998)
Changes in grazing management	0.07 – 1.9[i]	25 – 50 years	Follet et al. (2001)
Cropland conversion to grassland	0.9 – 1.9[j]	Not calculated	Eve et al. (2000)
Riparian buffers (nonforest)	0.4 – 1.0	Not calculated	Lal et al. (1998)
Biofuel substitutes for fossil fuels	4.8 – 5.5[k]	Saturation does not occur if fossil fuel emissions are continuously offset	Lal et al. (1998)

Note: Any associated changes in emissions of CH_4 and N_2O or—except for biofuels—fossil fuel CO_2 are not included.

[a] Values are for average management of forest after being established on previous croplands or pasture.

[b] Values calculated over 120-year period. Low value is for spruce-fir forest type in Lake States; high value for Douglas fir on Pacific Coast. Soil carbon accumulation included in estimate.

[c] Values are for average management of forest established after clearcut harvest.

[d] Values calculated over 120-year period. Low value is for Douglas fir in Rocky Mountains; high value for Douglas fir in Pacific Northwest. No accumulation in soil carbon is assumed.

[e] Values represent the assumed CO_2 loss avoided in a single year (not strictly comparable to annual estimates from other options). Low and high national annual average per acre estimates based on acres deforested from National Resource Inventory (NRI) data and carbon stock decline from the FORCARB model, from 1990 to 1997.

[f] Selected example calculated over 100 years. Low value represents change from unmanaged forest to plantations for pine-hardwood in the mid-South; high value is change from unmanaged forest to red pine plantations for aspen in the Lake States.

[g] Both West and Post and Lal et al. estimates here include only conversion from conventional to no till. Estimates do not include fluxes of other associated GHGs.

[h] Tillage rates vary, but this value represents a central estimate by Lal et al. for no-till, mulch till, and ridge till.

[i] Low-end estimate is for improved rangeland management; high-end estimate is for intensified grazing management on pastures, which includes the return of plant-derived carbon and nutrients to the soil as feces.

[j] Assumed that carbon sequestration rates are same as average rates estimated for lands under the USDA Conservation Reserve Program (CRP).

[k] Assumes growth of short-rotation woody crops and herbaceous energy crops, and an energy substitution factor of 0.65 to 0.75. Potential for changes in other GHG emissions not included.

by extending the harvest age of the managed forests. Over time, a new and higher carbon equilibrium will be reached. Carbon sequestration rates due to forest management practices vary depending on the practice itself, tree species, climate, topography, and soil type (e.g., 2.1 to 3.1 t CO_2/acre/year as reported by Row (1996); see Table 2-1).

When a forest is harvested, some carbon is immediately released to the atmosphere via the logging operation or milling process (about one-half or two-thirds is emitted at or near the time of harvest, depending on the product and region), but some is tied up in wood products for a number of years. Carbon from wood products may be released to the atmosphere many years in the future as the wood products decompose, the timing of which will depend on whether the products are short-lived (e.g., paper) or long-lived (e.g., housing lumber), and whether those products are discarded in landfills. The carbon sequestration and emissions that result from the harvest-regeneration cycle, including the wood products pool, are captured in the analyses presented later in the report.

Forest management primarily affects carbon pools and associated atmospheric CO_2, rather than fossil fuel CO_2 and non-CO_2 emissions. Although it uses equipment to establish, cultivate, and harvest stands of trees, forestry is less energy-intensive than agriculture because the management interventions are spread out episodically over time—a handful of interventions at most over 20 to 50 years for managed stands, less for stands that remain unmanaged. Therefore, there is limited ability to reduce energy-related CO_2 emissions in forestry. N_2O can be generated from forest fertilizer applications. However, relatively few forested acres receive fertilizer applications in a given year, so the aggregate effect of forestry on N_2O emissions is quite small.[1]

A form of forest management that can avoid CO_2 emissions is *forest preservation*, sometimes referred to as forest protection or a harvest set-aside. This entails adopting a management regime that does not involve harvesting. Although CO_2 emissions from harvesting may be avoided, the enhancement of carbon storage will cease when the forest meets its biophysical equilibrium—when carbon inputs equal carbon outputs. The carbon stock then essentially becomes a static pool.[2] Preservation of this form foregoes the option to replace a steady-state forest with a net-sequestering young forest. However, as shown in Harmon et al. (1990) after timber harvests in the Pacific Northwest, the on-site carbon declines significantly and it takes over 200 years for a newly reforested area to attain the storage capacity of an old growth forest.

The GHG benefits of *reducing or avoiding deforestation* in many ways simply mirror those from afforestation. However, there may be significant differences in the timing of GHG effects. Under afforestation, it takes decades for carbon to accumulate in forest soils and biomass. The process of deforestation—clearing forestland for another use—may release a substantial amount of carbon into the atmosphere rapidly upon the time of harvest. Although some carbon may be transferred off-site in the form of harvested wood products, a substantial portion is released immediately in harvesting and manufacturing (Skog and Nicholson 2000), on the order of, say, 150 to 800 t CO_2/acre.

The USDA's Natural Resources Inventory (NRI) shows that 5.7 percent of the private forested land base in the United States was deforested between the years 1982 and 1997 (USDA NRCS 2000), at an

[1] N_2O emissions associated with fertilization of forest soils are estimated to be 0.4 Tg CO_2 Eq. in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2003* (EPA 2005). These emissions are not included in the analyses presented in later chapters. According to EPA (2005), the rate of fertilizer application for the area of forests that receives fertilizer in any given year is relatively high. However, average annual applications are quite low (inferred by dividing all forestland by the amount of fertilizer added to forests in a given year).

[2] A mature forest, however, is not a static or unchanging carbon source; it is just that the net rate of sequestration is on average unchanging. But some studies suggest that even very old forested stands continue to sequester carbon (Lugo and Brown 1986, Phillips et al. 1998, Phillips et al. 2002a).

average annual rate of 241,147 acres per year. The primary conversion of forestland was to pasture and developed lands.

Avoiding or reducing deforestation does not necessarily imply that harvests will never occur. Rather, land can be retained in forested use and still be managed to produce timber through periodic harvesting. The process of eliminating harvests altogether is referred to as forest preservation or forest protection, as discussed above.

Agricultural Soil Carbon Sequestration

Croplands often emit CO_2 as a result of conventional tillage practices and other soil disturbances. Soils containing organic material that would otherwise be protected by vegetative cover are exposed through conventional tillage practices and become susceptible to decomposition. Frequent or intense tillage breaks down soil macroaggregates, thereby enhancing the exposure of carbon to microbial activity. This added soil exposure also enhances decomposition by raising the soil temperature (Lal et al. 1998). Adopting conservation tillage practices, changing the overall land and crop management, modifying cropping intensity, or retiring marginal lands from production can reduce or eliminate this exposure, thus reducing or eliminating the associated CO_2 emissions. Given widespread adoption of the management options discussed here, agricultural soils may be able to contribute more than a reduction in emissions; they have the potential to become a net sink of CO_2. These options are discussed briefly below.

In the United States, conservation tillage is typically defined as any tillage system that maintains at least 30 percent of ground covered by crop residue after planting (CTIC 1994). Conservation tillage eliminates one or several of the practices associated with conventional tillage, such as turning soils over with a moldboard plow and mixing soils with a disc plow (Lal et al. 1998). Conservation tillage practices, including no till, ridge till, and minimum till, allow crop residues to remain on the soil surface as protection against erosion.

Current estimates for CO_2 gains from conservation tillage range from about 0.6 to 1.1 t/CO_2/acre/yr, with differences in the estimated saturation period (West and Post 2002, Lal et al. 1998). A compilation of study results by West and Post (2002) suggests that soil carbon accumulation after adoption of conservation tillage typically occurs for periods of 15 to 20 years and then returns to a soil carbon steady state with no additional gains in carbon. Studies suggest that agricultural soils in the United States, on aggregate, have not reached a biophysical saturation point (IPCC 2000, Donigian et al. 1995, Kern and Johnson 1993). Further information on carbon saturation and reversal issues is provided below.

A final option aimed at reducing the potential decomposition of organic material is the retirement of economically marginal lands from production. Removing these lands from production can reduce CO_2 emissions, as well as N_2O emissions associated with fertilizer applications. Depending on the new land cover of these retired lands, they can become a carbon sink. Lands are often retired through federal programs such as the USDA Conservation Reserve Program (CRP).

Grassland Conversion

Grassland conversion refers to converting existing cropland to grasslands or pasture. Because there is continuous vegetative cover, the retention of soil carbon is higher than that for conventionally tilled cropland. Grassland conversion often involves cropland needing conservation treatments and may be part of a conservation program, such as CRP. Sequestration from this activity can vary from about 0.9 to 1.9 t CO_2/acre/yr (Eve et al. 2000, Table 2-1).

Grazing Management

While expanding grassland area can enhance carbon storage, further sequestration may be possible from improving the way grasslands are used for livestock grazing. Sequestration can be enhanced by increasing the quantity and quality of forages on pastures and native rangelands and by reducing carbon losses through the degradation process, thereby retaining higher soil carbon stocks (IPCC 2000). The range of mitigation estimates for grazing practices is wide, and the applicability of these numbers to the United States is a topic of ongoing research.

Grazing management practices can have multiple GHG effects. For instance, the quality of forage can affect livestock digestion processes and the amount of CH_4 that is emitted through enteric fermentation. Additionally, if nutrient inputs, in particular nitrogen-based fertilizers, are needed to enhance forage stocks, this can generate N_2O emissions post-application. The CH_4 and N_2O implications of livestock practices are addressed in more detail below.

Riparian Buffers

The establishment of riparian buffers can be viewed as a special case of either afforestation, forest management, or grassland conversion and thus fall under either forestry or agriculture. These practices are of particular interest because of their potential water quality co-benefits. Riparian buffers involve the establishment or maintenance of coarse vegetative land cover (trees, brush, grasses, or some mixture) on land near rivers, streams, and other water bodies. These actions are often focused around areas being cultivated or developed and used to filter the runoff of sediment, nutrients, chemicals, and other compounds that may impair water quality. Local, state, or federal government or private company guidelines often mandate that existing riparian buffers be left intact during timber harvests. Establishing or protecting these buffers can sequester CO_2 in the soil from the accumulation of organic material and in vegetative biomass if the buffer is planted or vegetation migrates into the area. This option also reduces baseline emissions from agriculture if the total cultivated area declines.

In 1997, a total of 199,600 acres of field borders and filter strips were in place on cropland, and a total of 1.6 million acres of grassed waterways existed (Uri 1997).

GHG Emissions Reduction Options in Agriculture

This section presents the agricultural mitigation options that can directly reduce CO_2, CH_4, and N_2O emissions, separate from the carbon sequestration options discussed above. CO_2 emission reduction options are discussed first; then the section addresses options to reduce non-CO_2 gases.

Reduction of CO_2 Emissions from Fossil Fuel Use

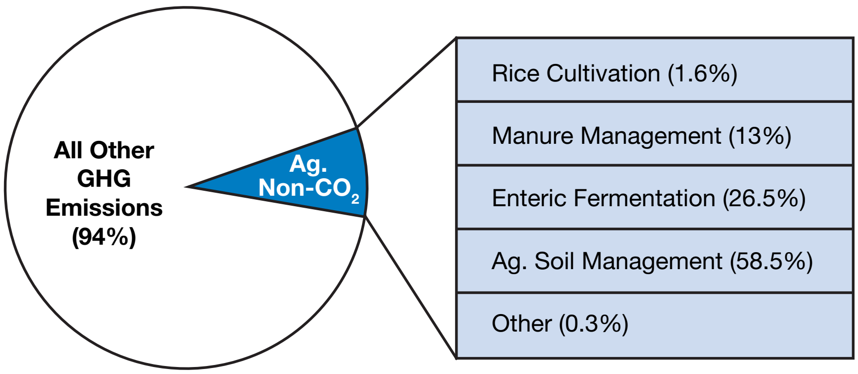
The main direct source of CO_2 emissions from U.S. agriculture is on-farm fuel use, although there are upstream releases related to the manufacture of equipment, fertilizer, and other agricultural inputs. Changes in practices that reduce the use of energy-intensive inputs can reduce CO_2 emissions from this sector. In the analysis presented in subsequent chapters, the CO_2 emissions captured because of agricultural management changes include emissions from direct use of fossil fuels in farm equipment, water pumping, and grain drying and fossil fuel use in fertilizer and pesticide production. For the purposes of this report, these emission reductions are associated with agricultural-sector activity, but other reports (e.g., annual EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks*) may consider these emissions associated with the energy or manufacturing sector.[3]

Reduction of Non-CO_2 GHG Emissions

Agriculture is a major source of non-CO_2 GHGs emissions, and the emissions can be reduced in numerous ways through changes in management practices. The GHGs of primary concern in the agriculture sector are N_2O and CH_4. These agricultural gases account for 433 Tg CO_2 Eq./year or over 6 percent of total U.S. GHG emissions (EPA 2005). Figure 2-1 displays the relative contribution of these activities and compares them to total U.S. GHG emissions. The relative potency of N_2O and CH_4 as climate change gases is greater than CO_2 on a per-unit basis (see Box 1-1 in Chapter 1).

[3] Please note that this report does not consider emissions from fossil fuel use in the forestry sector because of insufficient data on these emissions.

Figure 2 1: Agricultural Non CO_2 Emissions by Source Relative to All Other GHG Emissions



Source: EPA (2005).

N_2O emissions from agriculture account for just over 270 Tg CO_2 Eq./year or 63 percent of agricultural non-CO_2 emissions. Agricultural N_2O is largely tied to fertilizer application, nitrogen-fixing plants such as legumes, and manure emissions. Therefore, reductions can be accomplished by reducing nitrogen-based fertilizer applications, using nitrogen inhibitors, improving nitrogen nutrient management, altering crop mix, and reducing nitrogen content of animal feeds (McCarl and Schneider 2000). Economic incentives to reduce GHGs can alter the relative price of inputs and management practices that generate non-CO_2 emissions. The economic model used in this report accounts for these changes in prices (costs) and modifies practices and reduces emissions accordingly in the analyses that follow.

CH_4 emissions account for 161.4 Tg CO_2 Eq. per year or 37 percent of agricultural non-CO_2 emissions and are due in large part to emissions from livestock manure and enteric fermentation in the digestive tracts of ruminant livestock (see Table 2-2). Changes in feeding ratios and manure management strategies can be undertaken to reduce these emissions. Rice cultivation is also a source of CH_4 emissions, although less so in the United States than in other parts of the world. CH_4 uptake and emissions from cropland soils are not well understood and are not included in the EPA GHG inventory reports or in this analysis. The following sections outline four major sources of agricultural non-CO_2 emissions and potential mitigation options.

Table 2-2: Agricultural Non-CO_2 Emissions by Source, 2003 (Tg CO_2 Eq.)

Emission Source	CH_4	N_2O	Total Non-CO_2
Agricultural soil management	—	253.5	253.5
Enteric fermentation	115.0	—	115.0
Manure management	39.1	17.5	56.6
Rice cultivation	6.9	—	6.9
Field burning of agricultural residues	0.8	0.4	1.2
Total emissions from agriculture	161.8	271.5	433.2

Source: EPA (2005).

Agricultural Soil and Fertilization Management

N_2O emissions are produced in soils through the processes of nitrification (aerobic microbial oxidation of ammonium [NH_4] to nitrate [NO_3]) and denitrification (anaerobic microbial reduction of nitrate to di-nitrogen [N_2]). Agricultural soil N_2O emissions represent 58 percent (253.5 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2). The application of nitrogen-based fertilizers to croplands is a key determinant of N_2O emissions, because excess nitrogen not used by the plants is subject to gaseous emissions, as well as leaching and runoff. A viable mitigation option to reduce soil N_2O emissions is to adopt management practices that ensure the most efficient use and application of nitrogen-based fertilizer while maintaining crop yields.

Enteric Fermentation

The primary source of CH_4 emissions, which represents 27 percent (115.0 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2), is ruminant livestock and the microbial fermentation process of feed in their digestive system (rumen). The amount of CH_4 emitted from an animal depends primarily on the efficiency of the animal's digestive system, which is determined by the animal's feed or diet.

Viable options are available for reducing CH_4 emissions from enteric fermentation, because CH_4 releases essentially represent wasted energy that could otherwise be used to produce milk or beef. Direct approaches attempt to increase the rumen efficiency, thus reducing the amount of CH_4 produced per unit of feed. Indirect options focus on increasing animal productivity, reducing the amount of CH_4 emitted per unit of product (e.g., milk, beef). These direct and indirect approaches include options for improving the feed-intake efficiency (e.g., use of bovine somatotropin [bST]), altering livestock management practices (e.g., elimination of stocker phase in beef production), and using intensive grazing.

Manure Management

Livestock manure can produce both CH_4 and N_2O emissions. The level of CH_4 emissions depends on the way the manure is handled and stored. In many livestock operations in the United States, animals are raised in confined areas, and their manure is diverted to holding areas for further management. CH_4 is produced by the anaerobic decomposition of manure that is stored in lagoons, ponds, pits, or tanks. N_2O is produced through the nitrification and denitrification of the organic nitrogen in livestock manure and urine. The combined CH_4 and N_2O emissions from livestock manure represent 13 percent (56.6 Tg CO_2 Eq.) of agricultural non-CO_2 emissions (Table 2-2).

Anaerobic digesters that cover and capture the CH_4 emitted from collected manure, and potentially used as an on-farm energy source, represent a key mitigation option. The specific storage system will determine the type of digester or digestion process that will be applied to the manure (e.g., plug and flow, unheated or heated lagoon, complete mix). The emitted gas can either be converted into electricity for use as an on-farm energy source or consumed through flaring the collected gas. In either case, CH_4 is mitigated and CO_2 is released, but this option still remains a viable option for net GHG reductions because the GWP for CH_4 is 21 times higher than CO_2. Another CH_4 mitigation option allows for aerobic decomposition of manure as a solid on pasture-, range-, or paddock lands.

Rice Cultivation

Rice production under flooded conditions results in CH_4 emissions through the anaerobic decomposition of organic matter in the fields. Approximately 90 percent of the world's harvested rice area is grown under this management practice for some period of time (Wassman et al. 2000). In the United States, all rice is cultivated under flooded conditions (EPA 2005), but rice CH_4 accounts for less than 2 percent (6.9 Tg CO_2 Eq.) of U.S. agricultural non-CO_2 emissions (Table 2-2). Mitigation options for rice CH_4 include changes in water management regime, the use of inorganic fertilizers, and different cultivar selection. In the analyses presented later in the report, rice CH_4 is reduced through decreases in rice acreage.

Biofuel Offsets of Fossil Fuels

Products from the forest and agriculture sectors can mitigate GHGs by serving as substitutes for fossil fuels or for products that depend on fossil fuel combustion in their production. Though these options do involve forest and agricultural carbon sinks, the primary GHG benefits of these options can generally be treated as equivalent to permanent emission reductions.

A potential process for reducing atmospheric CO_2 is the cultivation of perennial grasses, short-rotation woody crops, or traditional crops for biofuel production. The production of these alternative energy sources created from biomass has the potential to reduce the use of fossil fuels used in the power generation and transportation sectors, the largest sources of CO_2 emissions in the United States.

The essential premise of biofuel as a means to reduce GHGs is based on their renewability. Biofuels, like fossil fuels, release GHGs when burned for energy production. However, biofuels are releasing GHGs (CO_2) that have been removed from the atmosphere through photosynthesis and stored in biomass. In essence, the plants are harvesting GHGs for use in energy production. In a steady state of biofuel production and use, there is little to no net addition to atmospheric GHG concentrations. However, fossil fuel combustion transfers carbon to the atmosphere that was stored underground in coal, petroleum, or natural gas reserves without replacing the fossil carbon stock and thereby, on net, raises GHG concentrations.

Specific examples of biofuel options include using forestry and agricultural residues and planting dedicated energy crops such as switchgrass or poplar to use as feedstock for electric power generation. In 2002, biomass accounted for only 1 percent (37 billion kilowatt hours) of U.S. electricity generation and is projected under baseline conditions to remain at 1.3 percent of generation (81 billion kilowatt hours) by 2025 (Energy Information Administration [EIA] 2004). In analyses presented later in this report, emission reductions due to biofuels used in power generation result from comparing net GHG emissions of coal-fired plants to net GHG emissions of biomass-fired plants. Using biofuels as a supplement to coal in co-fired plants is also possible. Finally, corn can be grown to produce ethanol as replacement for liquid fossil fuels (though this latter option generates little GHG mitigation in this report's analysis).

Unique Time Dynamics of Carbon Sequestration Options

Forestry and agriculture practices that preserve and enhance carbon storage in soils and biomass exhibit unique and important features compared to mitigation activities in all sectors of the economy that reduce fossil fuel CO_2, CH_4, N_2O, and emissions of other GHGs. The primary distinguishing characteristics are mainly related to the unique temporal dynamics of sequestration options.

Comprehensive GHG accounting of sequestration options requires the inclusion of both sequestration and release of CO_2 and sometimes CH_4 and N_2O. This tracking needs to occur over long timeframes both during normal land-use and management practices and in mitigation activities. Three fundamental factors need to be considered: the slowdown or so-called *saturation* (or approach to equilibrium) of sequestration rates, the potential for *reversal* of carbon benefits if sequestered carbon is re-released into the atmosphere at some future point in time, and the fate of carbon in long-lived products after the time of harvest. These issues of carbon permanence are addressed briefly below and more thoroughly again in Chapter 6.

"Saturation" of Carbon Sequestration to Equilibrium

The amount of carbon that can be sequestered in agricultural soils and forest ecosystems is ultimately constrained by biophysical factors. Once a sequestration activity such as afforestation or crop tillage change takes place, the rate of the ecosystem's carbon inputs exceeds the rate of its carbon outputs, thereby leading to a net accumulation of carbon stocks on-site. However, the biophysical processes evolve over time until the rate of carbon output just equals the rate of carbon inputs. At that point, the system has reached a new carbon equilibrium, and no net carbon stock accumulations can be expected beyond that point. In broad discussions of carbon sequestration strategies, this process is typically referred to as carbon "saturation."[4]

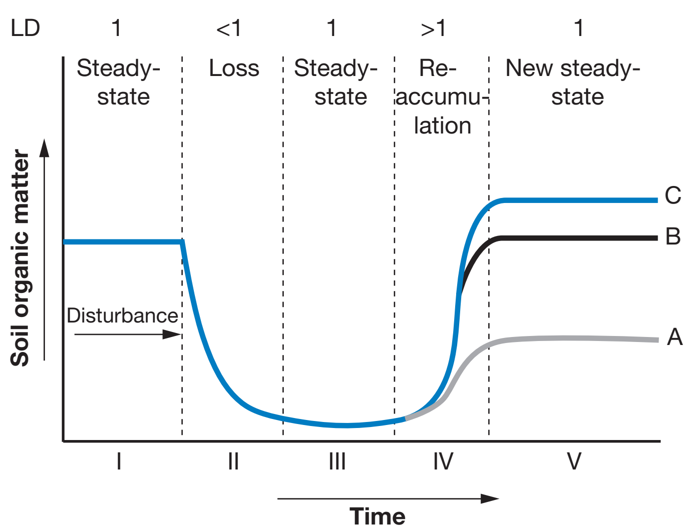
The time it takes to reach this steady state varies across soil types, site conditions, and management practices. A key determinant of saturation time is the land-use history of a given parcel—when anthropogenic and natural disturbances occurred, what land-use practices were involved, and how long they persisted. If soils in the northern Corn Belt, for example, were first tilled from native grasslands with a given soil organic matter (SOM) content in the early 20th century, cropped using conventional tillage practices, and then converted to lower-tillage practices, this land-use history will strongly influence the level of SOM in the soils today. Further, alternative management of these soils to enhance SOM levels will be limited by the difference between the current SOM level and the potential or original level (see Figure 2-2).

Studies of soil conservation tillage effects on carbon sequestration range from relatively quick adjustment to steady state (e.g., 15 to 20 years [West and Post 2002] to longer saturation periods in excess of 50 years [Lal et al. 1998]; see Table 2-1). The West and Post (2002) analysis reviews studies of SOM changes from tillage and concludes that, in most cases, saturation is reached at about 15 years, with some residual carbon uptake after that period.

Figure 2-3 summarizes their analysis. Based on their work, the analyses presented later in this report use a soil saturation assumption of 15 years.

Forest carbon sequestration tends to saturate over longer periods of time, 80 years or more after stand establishment in the United States, varying by

Figure 2 2: Conceptual Model of Soil Organic Matter Decomposition and Accumulation Following Disturbance

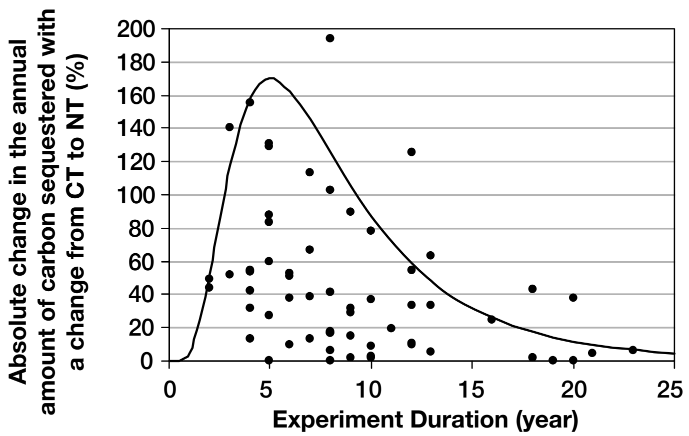


Note: At steady state (II), carbon (C) inputs from litter (L) equal C losses via decomposition (D) (i.e., L/D = 1). After a disturbance, D often exceeds L, resulting in loss of C (II), until a new, lower steady state is reached (III). Adoption of new management, where L exceeds D results in a reaccumulation of C (IV) until a new, higher steady state is reached (V). The eventual steady state (A, B, or C) depends on the new management adopted.

Source: Figure 4-5 in Kauppi and Sedjo (2001), drawn from work of Johnson (1995) and IPCC (2000).

[4] It is necessary to make a scientific distinction between saturation, which refers to the ultimate biophysical limits to growth of an ecosystem, and equilibrium, which refers to a system in steady state where inputs equal outputs. The latter is a subset of the former. In other words, some systems can be in equilibrium, but not be at their biophysical saturation point, but if a system is at its saturation point, it is also in equilibrium. By and large, our discussion of sequestration dynamics refers to the time it takes for a system to reach its new equilibrium point after a land-use or land management change. In some cases, this new equilibrium will not reflect the ultimate biophysical saturation point. However, to maintain consistency with typical word choice, we use the term "saturation" to reflect the broad process of reaching a new equilibrium. For further discussion on the issue of soil carbon saturation, see West and Six (2005).

Figure 2 3: Absolute Change in the Annual Rate of Carbon Sequestered Following a Change from Conventional Tillage (CT) to No Till (NT)



Note: Estimates are relative to soil carbon values under CT over the experiment duration, which means the estimated change in annual sequestration is greater if carbon under CT is declining while carbon under NT is increasing. Values in the figure are absolute (no negative values) and represent the percentage change in the estimated annual sequestration rate, not the percentage change in soil carbon. The method for calculating this value is outlined by West and Post (2002). A nonlinear regression curve has been fitted to the data, as described by West et al. (2004), to indicate the estimated peak and duration of soil carbon sequestration. This estimate represents the potential to sequester carbon, and soils or environments that have limiting factors that decrease or inhibit soil carbon sequestration are represented by values below the curve. Values considered as statistical outliers are not shown in the figure.

Source: West and Post (2002).

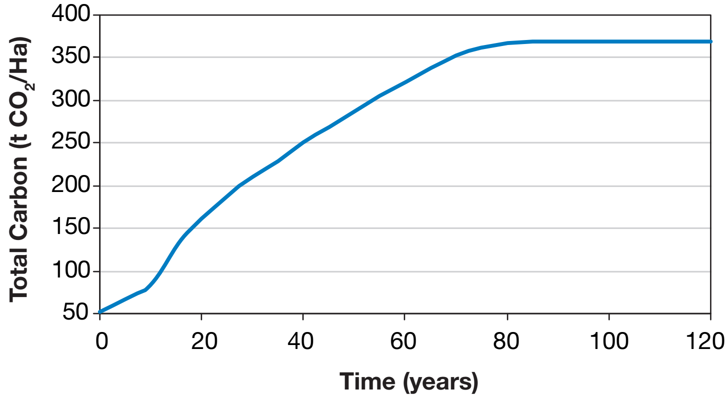
forest type and site class (Birdsey 1996). Figure 2-4 illustrates a typical carbon growth pattern following conversion of agricultural lands to a pine plantation in the U.S. South. However, research has shown that old growth forests in the United States (e.g., Douglas fir or redwood stands in the Pacific Northwest Westside [Harmon et al. 1990] and in the tropics) may continue to accumulate carbon for hundreds of years, although at a decreased rate (Lugo and Brown 1986, Phillips et al. 1998, Phillips et al. 2002a, 2002b).

Saturation has important implications for assessing forestry and agricultural sequestration in the United States, as saturation rates vary across carbon pools, activities and land conditions. In the long run, though, the rate at which activities accumulate carbon at certain periods of time is not as critical to climate change mitigation as the maximum, cumulative carbon storage potential of the alternative land use. Saturation is a dynamic phenomenon as well and may respond to climate and/or future environmental and technological change.

Reversibility of Carbon Sequestration

The accumulated carbon from forestry and agricultural sequestration practices can be re-released back to the atmosphere through either natural or

Figure 2 4: Carbon Accumulation on an Afforested Stand to Saturation



Notes: 1) Saturation reached in about year 80, and no additional carbon sequestration afterward. 2) Soils contain 50 t CO_2 of soil organic matter in year 0.

Source: Birdsey (1996).

intentional disturbances, such as fires, management changes, or logging. The climate benefits of carbon sequestration activities are therefore potentially reversible. This is sometimes referred to as the permanence or duration issue. Note that even if incentives for carbon sequestration, such as those evaluated later in this report, cause harvests to be delayed, harvesting may still occur eventually unless expressly prohibited by the incentive program or policy.

Designing approaches for carbon sequestration activities that appropriately capture the property rights for the sequestered carbon and the liabilities for carbon reversal remains a challenge. These issues are examined further as part of the discussions of Chapter 6.

Accounting for Carbon after Timber Harvests

When timber is harvested, some of the carbon that has accumulated over the years is removed from the site and the rest is left on-site to decay over time. The carbon that is removed from the site will at any time following the harvest be in one of the following carbon pools:

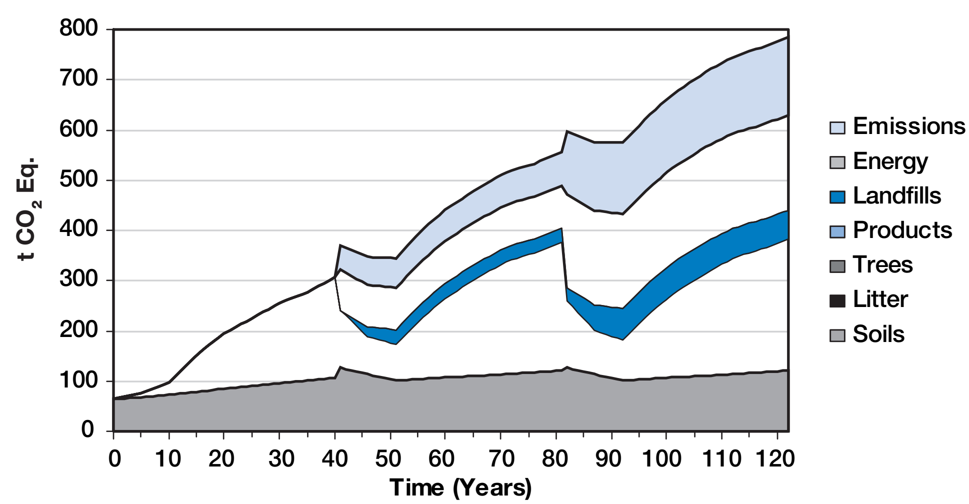
- products in use (very short-lived for paper, quite long for lumber);
- landfilled, often stored for extended periods; or
- atmosphere through combustion (sometimes to produce energy) or product decay.

Figure 2-5 illustrates the carbon flows over time under rotational forestry. In addition to the carbon fate after harvest discussed above, the figure shows the reaccumulation of forest carbon in on-site pools (trees, litter, soil) as a result of planting trees after each harvest. The figure illustrates that rotation forestry can continue to sequester carbon over extended periods of time through the continued accumulation of carbon stored in products and landfills. A complete accounting system should capture all of these product flows.

Addressing Carbon Sequestration Dynamics in this Report

In analyses presented later in this report, the dynamics of saturation, reversibility, and post-harvest destination of sequestered carbon are handled within the framework of the FASOMGHG model. As described in detail in Chapter 3, this model comprehensively accounts for both carbon sequestration and losses (i.e., sinks and sources) in forestry and agriculture over time, including harvested product pools. The accounting of both carbon sinks and sources occurs in the baseline and mitigation scenarios. Specific arrangements for addressing reversibility risk are discussed in Chapter 6.

Figure 2 5: Cumulative Carbon Changes for a Scenario Involving Afforestation and Harvest



Data Source: Birdsey (1996).

CHAPTER 3

Modeling Framework and Baseline

Chapter 3 Summary

The FASOMGHG model is used to evaluate the joint economic and biophysical effects of GHG mitigation scenarios in U.S. forestry and agriculture. This model includes all major GHG mitigation options in U.S. forestry and agriculture and accounts for changes in CO_2, CH_4, and N_2O, including carbon sequestration and emissions over time. The model also generates estimates of nutrient loadings and soil erosion in agriculture. FASOMGHG covers private timberlands and all agricultural activity across the conterminous ("lower 48") United States, broken into 11 regions, and tracks five forest product categories and more than 2,000 production possibilities for field crops, livestock, and biofuels. FASOMGHG runs simulations for 100-year periods and reports results on a decadal basis. The model simulates the actions of producers and consumers with perfect foresight of future demands, yields, technologies, and GHG prices.

Mitigation analyses presented later in this report pivot off a FASOMGHG baseline (business as usual) projection of future economic and GHG effects. This baseline estimates that private forests will constitute a net carbon sink for several decades, though the sink is projected to diminish over time. Direct (including N_2O and CH_4) and indirect sources and sinks in the forest and agriculture sectors constitute a net emission source in the baseline of 270 Tg CO_2 per year in the 2010 decade. This net baseline emission rate nearly doubles by around 2030 and then stabilizes somewhat thereafter. This pattern is largely dictated by carbon sink dynamics.

This chapter first presents the modeling framework and data employed by the FASOMGHG model of the U.S. forest and agriculture sectors, which is the analytical foundation for this report. After describing model details, the chapter moves to the FASOMGHG business-as-usual (BAU) baseline, focusing on future projections of GHG emissions and sequestration in the U.S. forest and agriculture sectors. The FASOMGHG baseline is evaluated against recent trends in land use, GHG emissions and sequestration, and baseline projections developed by other recent studies.

Modeling Framework

Examining the dynamic role of forest and agricultural GHG mitigation requires an analytical framework that can depict the time path and GHG consequences of forestry and agricultural activity. To credibly model or simulate baseline and additional mitigation effects in these sectors, it is critical to have as complete coverage as possible along several key dimensions:

Sectoral

- Sufficient detail to identify targeted economic opportunities within and across the sectors (e.g., land-use change, forest management, agricultural management, biofuel production).

- Inclusion of market-clearing processes and resource competition needed to show the commodity market (forest and agricultural products) feedback effects of mitigating GHGs in forestry and agriculture.

Spatial

- Heterogeneity of biophysical and economic conditions within and across regions as it relates to the production of food, fiber, fuel, and the GHG consequences thereof. For instance, regional carbon sequestration rates can vary spatially by more than an order of magnitude.
- Competition for region-specific resources, such as land and water, which affects economic responsiveness in forestry and agriculture to traditional commodity market signals and to GHG economic incentives.

Temporal

- Ability to capture dynamic biophysical processes (e.g., soil and biomass carbon accumulation over time, fate of harvested wood products).
- Ability to capture dynamic economic processes (investment, technological progress, demand trends, traditional commodity, and GHG market developments).

In addition, models used for policy evaluation should, to the extent possible, be calibrated to and validated by observed economic and biophysical phenomena. FASOMGHG encompasses the dimensions just defined and thereby provides an analytical foundation to address the issues raised in this report. This section of the report describes FASOMGHG's conceptual framework, scope of coverage, data, and other details.

General Model Description

FASOMGHG is an augmented version of the Forest and Agricultural Sector Optimization Model (FASOM) (Adams et al. 1996) as developed by Lee (2002). The model has all of the forest- and agriculture-sector economic coverage of the original FASOM model unified with a detailed representation of the possible mitigation strategies in the agriculture sector adapted from Schneider (2000) and McCarl and Schneider (2001).

FASOMGHG is a 100-year intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the forest and agriculture sectors in the United States. The model solution portrays a multiperiod equilibrium on a decadal basis. The results from FASOMGHG yield a dynamic simulation of prices, production, management, consumption, and GHG effects within these two sectors under the scenario depicted in the model data.

FASOMGHG can simulate responses in the U.S. forest and agriculture sectors to economic incentives such as GHG prices or mitigation quantity targets. Economic responses include changes in land use between and within the sectors and intrasectoral changes in forest and agricultural management.

FASOMGHG's key endogenous variables include

- land use;
- management strategy adoption;
- resource use;
- commodity and factor prices;
- production and export and import quantities; and
- environmental impact indicators:
  - — GHG emission/absorption (CO_2, CH_4, N_2O) and
  - — surface, subsurface, and groundwater pollution for nitrogen, phosphorous, and soil erosion.

Table 3-1 summarizes FASOMGHG's key dimensions. The remainder of the section provides more detail on the model's structure, data, and key parameters.[1]

[1] For more complete model detail on FASOMGHG and its affiliated models, consult Dr. Bruce McCarl's Web site, (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm).

Table 3-1: FASOMGHG Model: Key Dimensions

Model Dimension	Forest Sector	Agriculture Sector
General scope and coverage		
Geographic coverage	Land coverage for conterminous United States with other regions linked by international trade	Same
Regional detail	11 U.S. regions, 9 of which produce forest goods	11 U.S. regions, 10 of which produce agricultural goods
Land ownership coverage	All private timberland in conterminous United States	All agricultural land in major commodity production in the conterminous United States
Economic dimensions		
Economic modeling approach	Optimizing producer and consumer behavior over finite time horizon	Same
Time horizon	Model base year = 2000 Resolution = 10-year time steps Typically run for 100 years	Same
Discount rate	4%	Same
Commodities	10 commodities 5 products: sawlogs, pulpwood, fuelwood and milling residues (2) 2 species: softwood and hardwood	48 primary products 45 secondary products
Price and cost data	Resource Planning Act (RPA) assessment (USDA Forest Service 2003)	USDA NRCS data with updates based on *Agricultural Statistics*
Supply/land inventory	USDA Forest Service Forest Inventory and Analysis Data	USDA NRI, Agricultural Census, and NASS data
Supply/biophysical yield	USDA Forest Service ATLAS model (Mills and Kincaid 1992)	Crop budgets and EPIC (Williams et al. 1989) model simulations
Demand	Adapted from demand models used in latest RPA Assessment (USDA Forest Service 2003)	Variety of demand studies (see "Agricultural Product Demand" on page 3-9)
International trade	10 excess-demand regions facing each timber-producing region plus Canada	28 international regions for the main traded commodities plus excess supply and demand for others
Environmental variables		
GHG coverage	CO_2 as carbon sequestration in forest ecosystem pools and in harvested wood products	CO_2 sequestration and emissions CH_4 emissions N_2O emissions
Non-GHG environmental indicators	Timberland area by region, species, owner, age class	Agricultural land allocation Tillage practices Irrigation water use
	Forest management intensity	Cropland loadings of nitrogen, phosphorous, potassium, erosion, and pesticides

Geographic Coverage/Regional Detail

FASOMGHG covers forest and agricultural activity across the conterminous ("lower 48") United States, broken into 11 separate regions (see Table 3-2 and Figure 3-1).

The 11 regions are a consolidation of regional definitions that would otherwise differ if the forest and agriculture sectors were treated separately. The forest sector considers nine major production regions and agriculture distinguishes 10 regions.[2] The 11-region breakdown reflects the existence of regions for which there is agricultural activity but no forestry, and vice versa. For instance, the Northern Plains (NP) and Southwest (SW) regions reflect important differences in agricultural characteristics, but no forestry activity is included in either region. Likewise, there are important differences in the two Pacific Northwest regions (PNWW, PNWE) for forestry, but only the PNWE region is considered a significant producer of the agricultural commodities tracked in the model.

Land Base

FASOMGHG covers all cropland and pastureland in production throughout the conterminous United States. Livestock grazing is also tied to the use of animal unit months (AUMs) on public rangelands, largely in the western states. The model accounts for timber production from all U.S. forestlands, private and public, and timber imports. However, the forest-sector mitigation activities and GHG (carbon) accounting are limited to private timberland in the conterminous United States. Mitigation and carbon flows from public timberland and all forestlands too unproductive to be considered timberland are excluded from the model because of data limitations and because model development has heretofore focused on potential mitigation responses of the private sector to market-based incentives.[3] The potential impact of excluding public lands from the forest-sector analysis is addressed further below.

General Economic Concepts: Optimizing Behavior

At its heart, FASOMGHG solves a constrained dynamic optimization problem defined as follows:

Objective Function: Maximize the net present value (NPV) of the sum of producer and consumer surpluses across the forest and agriculture sectors over time (100 yrs), including any GHG payments introduced by a mitigation scenario.

Constraints:

- Total production = total consumption
- Technical input/output relationships hold
- Land-use balances

By maximizing the sum of producer and consumer surplus, the model ensures that all suppliers and demanders are making optimal choices about what to produce and consume. Because these choices occur over time, the optimizing nature of the model assumes that producers and consumers have *perfect foresight* regarding future demands, yields, technologies, and prices. See Box 3-1.

Given that the model is defined for a finite period, there will be immature trees of some age at the end. If the model did not place a value on these forests, the optimizing nature of the model would be inclined to deplete all timber at the end of the projection period rather than leave it around for future harvests. Similarly, agricultural land values at the end of the period must also be considered to ensure that land is not inappropriately converted as a result of a perceived lack of opportunity cost. To counter these ending-period anomalies, *terminal conditions* are imposed on the model that value ending immature trees and land remaining in agriculture. FASOMGHG assumes that forest management is, from the last period onward, a continuous or constant flow process with a forest inventory that is "fully regulated" on rotations equivalent to those observed in the last decades

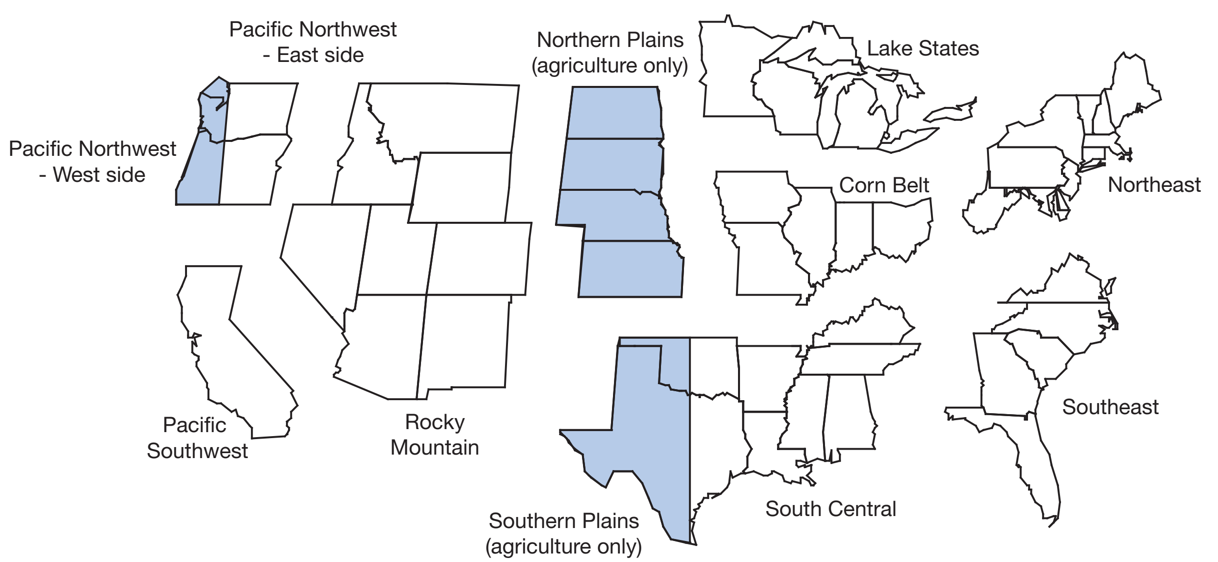
[2] The 10 agricultural regions in FASOMGHG are an aggregation of the 63 agricultural regions considered in the agriculture-only version of this model (ASMGHG) (Schneider 2000).

[3] Timberland is all land with forest cover capable of generating at least 20 cubic feet per acre per year of merchantable timber. Land with forest cover that does not meet this criterion is considered unproductive forestland.

Table 3-2: FASOMGHG Regional Definitions

Key	Name	States
CB	Corn Belt	Illinois, Indiana, Iowa, Missouri, Ohio
NP	Northern Plains	Kansas, Nebraska, North Dakota, South Dakota
LS	Lake States	Michigan, Minnesota, Wisconsin
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
PNWE	Pacific Northwest-east side	Oregon and Washington, east of the Cascade mountain range
PNWW	Pacific Northwest-west side	Oregon and Washington, west of the Cascade mountain range
PSW	Pacific Southwest	California
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
SC	South-Central	Alabama, Mississippi, Louisiana, Eastern Texas, Eastern Oklahoma, Arkansas, Tennessee, Kentucky
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SW	Southwest	Western Texas, Western Oklahoma

Figure 3 1: FASOMGHG Regions



Box 3-1: Perfect Foresight in Climate Economic Models

Three main approaches to economic modeling of climate change mitigation have been used in the past 2 decades. Engineering cost curves use activity data and cost data to compare and order mitigation practices of technologies by region from lowest to highest cost. Econometric approaches use revealed preferences of landowners for activity and cost data but do not include feedbacks in the land and commodity markets over time. Most climate economic models of multiple sectors, including FASOMGHG, use the third approach, dynamic simulation, which explicitly models economic decisions and market outcomes over time subject to an underlying behavioral or process model.

Weyant (2000) identifies foresight as a key element of structure for dynamic climate economic models, with two prevailing options: perfect and myopic. FASOMGHG employs the perfect foresight option, as do all but one of the climate economic models reviewed by Weyant. Perfect foresight assumes that agents, when making decisions that allocate resources over time (e.g., investments), know with certainty the consequences of those actions in present and future time periods.

Landowners understand that decisions they make today, such as converting agricultural land to trees, depend on their expectations of future prices and yields in forestry and agriculture and, in this case, prices and yields of GHGs. FASOMGHG simulates these decisions and employs these predictions to determine which actions should be taken today and which deferred to the future. As Weyant points out, this form of perfect foresight allows for an efficient allocation of resources over time. These perfect foresight models are also classified as dynamic optimization models. In contrast, myopic foresight uses no predictions of future prices and yields and uses only current information to make decisions that affect resource allocation over time, although not as efficiently as under perfect foresight.

In reality, investors have neither perfect foresight nor perfect myopia, so the modeling decision is not about which assumption is factually correct. In practice, perfect foresight is the approach preferred by most of the climate economic modeling community because of its consistency with economic theory and efficiency. But it is important to understand the implications of the modeling decision. In short, the costs of GHG mitigation estimated using perfect foresight models such as FASOMGHG will tend to reflect a more efficient mitigation response and thus be lower than costs estimated using a myopic foresight model.

of the projection (see Adams et al. [1996]). The terminal value of land remaining in agriculture is formed by assuming that the last period persists forever.

The multiperiod nature of the economic problem requires transforming future revenues and costs to the present using a real (inflation-adjusted) annual *discount rate*. The default rate used in FASOMGHG is 4 percent, which is broadly consistent with opportunity costs of capital in agriculture and forestry.

Forest-Sector Economic Detail

The forest-sector component of FASOMGHG is derived from the USDA Forest Service modeling system for performing periodic assessments of the nation's forests and related renewable resources under the Resources Planning Act (RPA). For more information on the RPA timber market modeling framework, see USDA Forest Service (2003).

Forest Commodities

FASOMGHG tracks the following five forest product categories:

- logs (3): sawtimber, pulpwood, fuelwood
- residues (2): logging and milling

These products are differentiated by two species types (softwood and hardwood) for a total of 10 forest commodities.

Forest Product Supply

Log supply in the model is based on a "model II" even-aged harvest scheduling structure (Johnson and Scheurman 1977) allowing multiple harvest age possibilities. The model's forest inventory is tracked by age, and the harvest responses are limited to even-aged management, wherein a forest stand is grown to a certain age and then harvested and regrown (unless land is allocated to another use after harvest). Timber harvests are responsive to the market price, discount rate, and growth rate of the forest stand. Log supply is volume harvested in each period, so endogenous decisions at the forest level are

[4] The forest production regions include 9 of the 11 regions identified in Table 3-2. The omitted regions are the Northern Plains and Southwest, which do not include any appreciable timber production.

- length of rotation,
- management regime to regenerate the harvested area, and
- species for regeneration.

Supply is segmented into two private-sector classes (industry and nonindustrial private) and nine regions within the United States.[4] Harvests from public lands are included in the model but are exogenously determined, rather than solved by the model.

Timber supply comes from harvests of the merchantable timber inventory existing at that time. The model's timber inventory data are derived from USDA Forest Service Forest Inventory and Analysis (FIA) field data. FIA is essentially a survey of U.S. forests, drawing data from approximately 70,000 field plots nationwide. These field plots have been sampled over time since the 1930s, with survey timing varying by region. The version of the FASOMGHG model used in this report is based on FIA data from the early 1990s.[5] The timber inventory is stratified by the following dimensions:

- region (9),
- land class defining suitability for movement between forestry and agriculture (5),
- ownership (2),
- forest type (4),
- site productivity class (3),
- timber management intensity class (4), and
- 10-year age classes (10).

For timber supply modeling purposes, the critical biophysical element of the timber inventory is the merchantable yield volumes. These volumes are tracked in the inventory data, and FASOMGHG models their evolution over time using the ATLAS model (Mills and Kincaid 1992), which essentially keeps inventory balances over time by tracking for each stratum in the inventory its volume growth, volume harvested, old area out, and new area in. Each stratum is represented by the number of timberland acres and the growing stock volume per unit area.

Forest Product Demand

The 10 forest commodities listed above are the raw materials produced by the forest sector that are ultimately used in the production of final products used by consumers. Therefore, forest commodity demand is characterized as a derived demand for these commodity inputs to the sector's final products. Final product demand is based on the Timber Assessment Market Model (TAMM) (Adams and Haynes 1996) for solid wood products and the North American Pulp and Paper (NAPAP) model (Zhang et al. 1996) for pulp and paper products.

The derived demand system starts with the demand for final products, which include the broad categories of lumber, plywood, oriented strand board (OSB), paper, paperboard, and market pulp, and the demand for wood as a fuel. Final product demand is converted to raw material demand (logs and residues) via physical conversion factors. Substitution is allowed between raw materials in a downward hierarchy from sawlogs to pulpwood to fuelwood, meaning that sawlogs can be used in lieu of pulpwood in pulp and paper production, but not vice versa. Likewise, pulpwood can be used in lieu of fuelwood, but not vice versa. Additionally, mill residues from sawlog processing can be used as a raw material to pulp and paper production. Total raw material demand is bound by sector processing constraints, which is also endogenous to the model.

The product demand functions shift over time as a function of

- macroeconomic factors (gross domestic product [GDP], population, labor force) and
- other key structural shifts:
  - — housing starts,
  - — pulp and paper technical factors (e.g., recycling), and
  - — log conversion factors.

[5] The model is currently being updated to reflect data from the early 2000s.

The macroeconomic and other structural shifts in demand are based on 50-year projections developed for the USDA Renewable Resource Planning Act Assessment and described in its supporting documentation (USDA Forest Service 2003).

International Trade in Forest Products

Canada is the dominant forest products trading partner with the United States, with Canadian exports accounting for a sizable share of total U.S. consumption of softwood lumber and some pulp and paper products, such as newsprint. Therefore, Canada-U.S. final product trade flows are treated explicitly in the model. Exports/imports from countries other than Canada are aggregated as price-sensitive net trade functions facing the U.S. regional markets. Future trade is projected to shift in response to exchange rate projections. The model assumes continuation of the current trade policy environment.[6]

Agriculture-Sector Economic Detail

The agriculture-sector component of FASOMGHG is derived from two predecessors, the Agricultural Sector Model (ASM) (Chang et al. 1992) and ASMGHG (Schneider 2000), both of which are static models of the U.S. agriculture sector. For consistency with the time dynamics introduced by the forest sector, economic decisions in the agriculture sector also conform to the intertemporal welfare maximization approach described above. Agricultural activity within each decade is assumed constant, with dynamic updating each decade based on USDA Economic Research Service (ERS) projections of future yield and consumption trends and past consumption and production trends, where available.

Table 3-3: Agriculture-Sector Commodities

Primary Products

- **Crops:** Cotton, corn, soybeans, soft white wheat, hard red winter wheat, Durham wheat, hard red spring wheat, sorghum, rice, oats, barley, silage, hay, sugarcane, sugarbeets, potatoes, tomatoes for fresh market, tomatoes for processing, oranges for fresh market, oranges for processing, grapefruit for fresh market, grapefruit for processing, rye
- **Animal products:** Grass-fed beef for slaughter, grain-fed beef for slaughter, beef yearlings, calf for slaughter, cull beef cows, milk, cull dairy cows, hogs for slaughter, feeder pigs, cull sows, lambs for slaughter, lambs for feeding, cull ewes, wool, unshorn lambs, mature sheep, steer calves, heifer calves, vealers, dairy calves, beef heifer yearlings, beef steer yearlings, dairy steer yearlings, heifer yearlings, other livestock, eggs, broilers, turkeys
- **Biofuels:** Willow, poplar, switchgrass

Secondary Products

- **Crop related:** Orange juice, grapefruit juice, soybean meal, soybean oil, high fructose corn syrup, sweetened beverages, sweetened confectionaries, sweetened baked goods, sweetened canned goods, refined sugar, gluten feed, starch, refined sugar cane, corn oil, corn syrup, dextrose, frozen potatoes, dried potatoes, chipped potatoes
- **Livestock related:** Fluid milk, grain-fed beef, grass-fed beef, veal, pork, butter, American cheese, other cheese, evaporated condensed milk, ice cream, nonfat dry milk, cottage cheese, skim milk, cream, chicken, turkey
- **Mixed feeds:** Cattle grain mix 0, cattle grain mix 1, high-protein cattle feed, broiler grain, broiler protein, cow grain, cow high protein, range cubes, egg grain, egg protein, pig grain, feeder pig grain, feeder pig protein, pig farrowing grain 0, pig farrowing grain 1, pig farrowing protein, pig finishing grain, pig finishing grain 1, pig finishing protein, dairy concentrate, sheep grain, sheep protein, stocker protein, turkey grain, turkey protein
- **Biofuels:** MMBtu of power plant input, ethanol, market gasoline blend, substitute gasoline blend

[6] For more on forest-sector trade and demand projection assumptions used in FASOMGHG, see USDA Forest Service (2003), Chapter 2.

Agricultural Commodities

The model's agriculture sector encompasses both primary production and secondary processing/ conversion, as indicated in Table 3-3.

Agricultural Product Supply

Primary commodity production is derived from allocation decisions based on a set of more than 2,000 production possibilities for field crops, livestock, and biofuels. The allocation decisions are based on optimizing across the budgets associated with each production possibility, given prices for outputs and inputs. Budgets are based on using inputs to produce a given level of outputs. Land is available in five cropland categories (based on erodibility) plus pastureland. The use of erodibility to classify cropland enables estimation of soil erosion and other environmental effects from different cropping and management practices, as reported in Chapter 7. The land inventory is fixed but can migrate back and forth between agriculture and forestry. Inputs are either regionally supplied subject to a price-sensitive input supply function (labor, grazing, and irrigation water) or nationally supplied at a fixed price (energy, agricultural chemicals, and equipment in more than 100 categories). Supply emanates from 10 regions within the United States.[7]

In the first 2 decades, the production solution is required to be within the combination of crop mixes observed historically, following a method developed by McCarl (1982), but is free to vary thereafter. Agricultural yields and factor usage vary by decade with USDA ERS-projected and historical trends in yield growth and input requirements to sustain this yield growth based on Chang et al. (1992).

Primary commodities are converted to secondary products via processing activities with associated costs (e.g., soybean crushing to meal and oil, livestock to meat and dairy). Processed products and some primary commodities are supplied to meet national-level demands. Once commodities are supplied to the market, they can go to livestock use, feed mixing, processing, domestic consumption, or export.

Agricultural Product Demand

The model uses constant demand elasticity functions to represent domestic and export demand. International agricultural demand is adapted from the USDA SWOPSIM model (Roningen et al. 1991). Domestic demand is drawn from many studies plus computations of arc elasticities from various other sources (Baumes 1978, Burton 1982, Tanyeri-Abur 1990, Schneider 2000, Hamilton 1985). Product demands are updated each decade based on USDA ERS projections and on historic trends where USDA data are unavailable.

International Trade in Agricultural Products

FASOMGHG has explicit trade functions between the United States and 28 distinct foreign trading partners for agricultural commodities having such detailed trade data available. For the remaining commodities traded internationally, excess supply/ demand functions are specified to capture net trade flows with the rest of the world as one composite trade region with the United States. Demand levels are parameterized based on SWOPSIM and USDA annual statistics.

Biofuels

For the purposes of this analysis, biofuels are treated as another agricultural commodity, but as shown in subsequent chapters of the report, they have a rather large potential for GHG mitigation within the sector and thereby warrant special attention. The data used in the analysis for biomass production conditions were mainly obtained from Oak Ridge National Laboratory (ORNL). The data from ORNL include average yields for the three biomass crops (willow, switchgrass, and hybrid poplar) and their corresponding farm-level production costs, varying by state. Estimates of hauling costs are added to the farm-level production costs to complete the budget data needed for the production model.

[7] The agricultural production regions match 10 of the 11 regions identified in Table 3-2. The omitted region is the Pacific Northwest-west side.

On the demand side, special consideration was given to the possibility that infrastructure limitations in the energy sector might impede rapid increase in market penetration for biofuel crops, given the very low use of biofuel crops to date. Therefore, market penetration constraints were imposed on biofuel demand for each decade in the model, with the initial constraints being relaxed over time as more capacity develops. These constraints were developed in consultation with staff from the U.S. Department of Energy's (DOE's) EIA, drawing on work from Haq (2002).[8]

Cross-Sector Land Interaction

A defining element of FASOMGHG is its ability to allocate land across and within the forest and agriculture sectors in response to economic and biophysical forces. As shown in Figure 3-2, the model includes four primary choices of land transfers: from forest to agriculture (cropland or pastureland), agriculture (cropland or pastureland) to forestry, cropland to pasture, and pasture to cropland. Many forested tracts are not suitable for agriculture because of topography, climate, soil quality, or other factors, so the model accounts for land that is not mobile between uses and land that is. Costs for converting forestland reflect differences in site preparation costs because of stump removal amounts, land grading, and other factors.

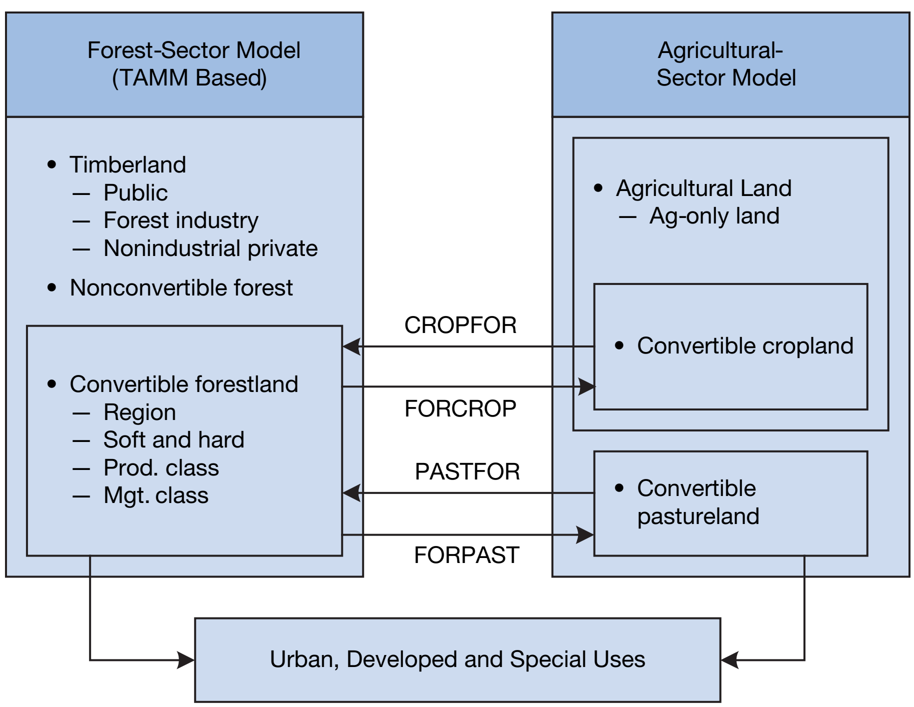
Greenhouse Gas Accounting

Table 3-4 lists the GHG sinks and sources covered by FASOMGHG by sector and gas.

Forest-Sector GHG Accounting

Forest ecosystem carbon accumulates in the forest in four distinct pools: trees, understory vegetation, litter, and soils. The allocation of carbon among these components varies by region, forest type, stand age, site quality, and previous land use. Within FASOMGHG, these allocations are derived from the USDA Forest Service FORCARB model (Birdsey 1992) and Turner et al. (1993). Critical among these relationships is the role of time.

Figure 3 2: FASOMGHG Market Linkages



[8] For more complete model detail on FASOMGHG and its affiliated models, consult Dr. Bruce McCarl's Web site, (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm).

As described in Chapter 2, once a forest is established, it typically accumulates carbon steadily for several decades, then the sequestration rate begins to decline. If the forest is left in place without harvest or other disturbance, the growth rate may eventually diminish when the forest reaches a steady-state equilibrium.[9] The carbon accounting component of FASOMGHG captures these nonlinear biophysical growth effects.

Additionally, forest carbon accumulates in harvested wood products after it leaves the forest. The carbon can reside in the products while they are being used (e.g., lumber and plywood in housing) or in landfills after the products are discarded and before they decompose and are re-released to the atmosphere. Storage in wood produces can continue for a very long time after harvest. The parameters used to allocate the wood product carbon destination over time after harvest are derived by the HARVCARB model (Row and Phelps 1991).

After it is harvested, carbon can be burned in the production process and released back to the atmosphere. If the burning occurs as part of a combustion process to generate bio-energy, the releases can be viewed as a form of fossil fuel substitution. This form of substitution could be accounted for differently than a normal emission release because it foregoes the transfer of below-ground carbon (coal, petroleum, gas) to the atmosphere, replacing it with "recycled" biofuel. Therefore, FASOMGHG tracks the amount of forest carbon burned for biofuel to examine policy scenarios under which this carbon is treated separately.

The combination of carbon accumulation in forest ecosystems, harvests, releases, product storage, and biofuel energy offsets can create an interesting carbon dynamic over time from the forest sector, as shown in Figure 3-3.

Agriculture-Sector GHG Accounting

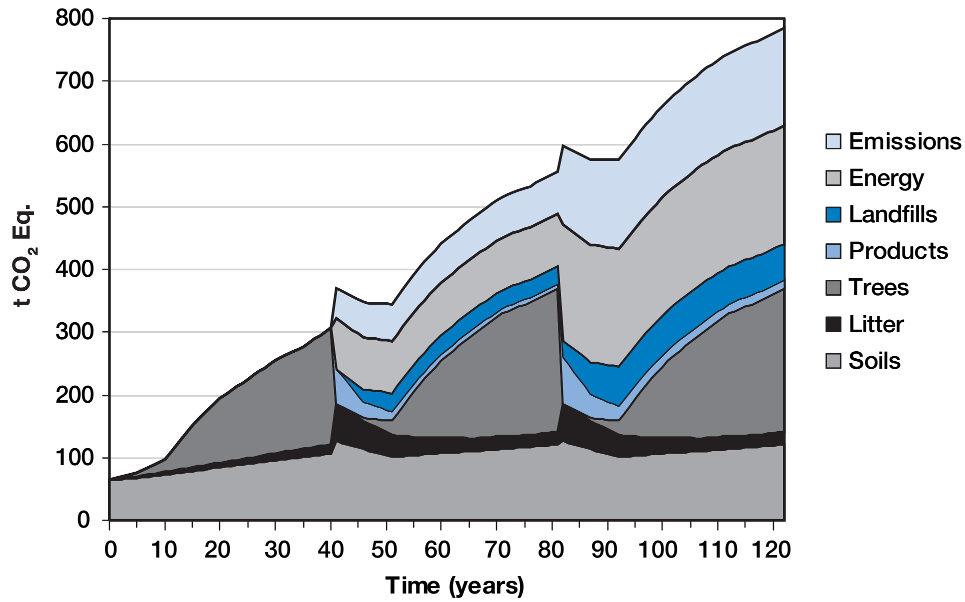
As with forests, carbon accumulates in agro-ecosystems; although in the case of U.S. agriculture, sequestration occurs largely in the form of soil organic carbon (SOC), rather than biomass. FASOMGHG captures SOC changes in response to cropping patterns and tillage changes, based on the CENTURY model (Parton 1996). Three types of tillage are depicted: conventional, minimum tillage, and zero tillage. Four different fertilization

Table 3-4: GHG Emission Sources and Sinks in FASOMGHG

Sector	CO_2 Sinks/Sources (biomass and soil carbon)	Fossil Fuel CO_2	CH_4 Sources	N_2O Sources
Forest	Carbon sequestration and release from forest ecosystems and harvested wood products	Biofuel use in wood processing as a fossil fuel emission offset		
Agriculture	Carbon sequestration and release from agro-ecosystem soils	On-farm energy use	Livestock manure	Fertilizer use
		Energy associated with inputs (e.g., fertilizer production)	Livestock enteric fermentation	Residue burning
		Biofuel production and use as a fossil fuel emission offset	Rice cultivation	Livestock manure

[9] As explained in Chapter 2, this carbon steady state is sometimes referred to as a "saturation point," but equilibrium is a more scientifically precise term. A site can be in steady state, with system inputs and outputs in balance and no net sequestration taking place yet still be able to yield more carbon if, say, inputs were increased by natural (CO2 fertilization) or artificial

Figure 3 3: Cumulative Carbon Changes for a Scenario Involving Afforestation and Harvest



Data Source: Birdsey (1996).

levels are also modeled, and crops are simulated by region. Soil carbon sequestration is assumed to occur at a constant rate for 15 years and then stabilizes thereafter, based on the work of West and Post (2002). Land can move to less intensive tillage with carbon gains or to more intensive tillage with carbon losses.

The agriculture sector releases CO_2 to the atmosphere through the on-farm use of fossil fuels as an energy source (tractors, irrigation, drying operations) and through the upstream emission of fossil fuels in the production of other material inputs such as agricultural chemicals using calculations from Schneider (2000) based on USDA data.

The agriculture sector is a major source of the non-CO_2 gases—CH_4 and N_2O. CH_4 releases in agriculture are from enteric fermentation, manure management, and rice cultivation. Enteric fermentation emissions and emission changes from the baseline are estimated using data based on EPA data and a set of alternatives proposed by Johnson et al. (2003a, 2003b), involving changes in feeding regimes, improved pasture use, and use of bovine somatrophine (bST). Manure emissions are estimated using swine and dairy farm data estimated for digester use based on EPA data. Rice CH_4 emission are estimated using data used to support the U.S. national GHG inventory (EPA 2003). N_2O sources in agriculture come from fertilizer use, residue burning, and livestock manure. These N_2O releases are estimated using U.S. activity data with IPCC emissions factors.

Difference in Scope of GHG Accounting in the Forest and Agriculture Sectors

Forest-sector GHG accounting in FASOMGHG does not include CO_2 emissions from on-site machinery and upstream processing of inputs, CH_4 emissions from forested wetlands or landfilled forest products, nor N_2O emissions from fertilizer use. Most of emissions data for these activities or sources are not readily available for the forest sector. Thus, the GHG accounting for the forest sector has a narrower scope than for the agriculture sector in FASOMGHG. However, the omitted emissions in the forest sector are generally thought to be small relative to those included, so their omission is unlikely to create a distorted view of mitigation potential in this report.

Non-GHG Environmental Indicators

Several variables discussed above provide useful information on environmental quality implications of modeled outcomes. In the forest sector, these include forest land area composition by species and age class, forest management intensity, and rotation length (harvest age). Land-use and management patterns are also reported on the agriculture side of the model. In addition, the model draws from the agricultural management model EPIC (Williams et al. 1989) to produce data on irrigated acres and water use and on cropland loadings of nitrogen, phosphorous, potassium, erosion, and pesticide use.

GHG Mitigation Strategies

The comprehensive coverage of FASOMGHG allows for the identification of several basic strategies for GHG mitigation in forestry and agriculture. Table 3-5 lists broad mitigation strategies aligned with specific mitigation activities tracked by FASOMGHG. These strategies are a mix of sequestration, emissions reduction, and fossil fuel offsets. Although each strategy has a focal GHG of interest, it is important to recognize that FASOMGHG incorporates multi-GHG accounting and therefore captures the net GHG consequences of each strategy. This is particularly critical given that GHG policies may include only a subset of GHGs, as discussed further in Chapter 5.

While FASOMGHG is fairly complete in its coverage of GHG mitigation opportunities in U.S. forestry and agriculture, some mitigation opportunities remain outside the scope of the model. Of those activities referenced in Chapter 2, two warrant further discussion here (see Table 3-6).

First, the model does not consider forest management opportunities on the 275 million acres (37 percent) of all forestland in the United States in public ownership (Smith et al. 2001). Assuming all of those acres could be managed to achieve the carbon enhancements for forest management

Table 3-5: Broad GHG Mitigation Strategies Covered in FASOMGHG

Strategy	Mitigation Activities Tracked in FASOMGHG	Target GHG
Afforestation	Convert agricultural lands to forest	CO_2
Forest management	Lengthen timber harvest rotation Increase forest management intensity Forest preservation Avoid deforestation	CO_2
Agricultural soil carbon sequestration	Crop tillage change Crop mix change Crop fertilization change Grassland conversion	CO_2
Fossil fuel mitigation from crop production	Crop tillage change Crop mix change Crop input change Irrigated/dry land mix change	CO_2
Agricultural CH_4 and N_2O mitigation	Crop tillage change Crop mix change Crop input change Irrigated/dry land mix change Enteric fermentation control Livestock herd size change Livestock system change Manure management Rice acreage change	CH_4 N_2O
Biofuel offsets	Produce crops for biofuel use	CO_2

Table 3-6: Mitigation Options Not Explicitly Captured in FASOMGHG

Option	Description	Maximum Biophysical Mitigation Potential	Economic and Other Adoption Factors
Forest management on public lands	Enhancing forest carbon through changes in management of publicly owned forestlands	~685 Tg CO_2 per year (275 MM acres at 2.5 t CO_2 per acre per year)	Public lands are by mandate managed for multiple uses, implying an opportunity cost of managing specifically for carbon. Allowable federal timber harvest levels set by Congress could have a large impact on baseline levels of carbon storage.
Grazing land management	Improving forage quantity and quality to retain more soil carbon	~590 Tg CO_2 per year (590 MM acres of nonfederal pasture/ rangeland at 1 t CO_2 per acre per year)	Limited data are available on the cost of adopting practices and corresponding carbon and other GHG effects.

referenced in Chapter 2 (roughly 2.5 t CO_2 per acre per year), this could hypothetically enhance forest carbon sequestration by nearly 700 Tg CO_2 per year.

However, this maximum biophysical potential estimate has little meaning. The biophysical productivity of public forestlands is generally lower than private lands, and this is an estimate of pure biophysical potential, without considering economic or other institutional factors. There is no information on the costs of achieving this mitigation on public forests. Moreover, the analyses in this report gauge the response of the forest and agriculture sectors to GHG prices or market incentives, essentially a private-sector phenomenon. Public land responses are possible but require public land management legislative mandates (e.g., changes in national or state forestland harvest or planting levels) that are fundamentally different from the market-based approaches addressed in this report.

Another set of strategies not captured in FASOMGHG is grazing land management practices. Grazing land includes rangeland, pastureland, and grazed forestland. The United States has about 590 million acres of nonfederal grazing land (USDA NRCS 2000). Little data exist on either the carbon sequestration effects or costs of these changes in practices. Using a mid-range estimate of 1 t CO_2 per acre per year for grazing practices from Chapter 2, this suggests a maximum biophysical potential for mitigation of nearly 600 Tg CO_2 per year. But again, little data are available from which to conduct economic analyses of these options. In addition, changes in grazing practices could be adopted on federal lands, but limited information is available on the area of land to which these practices could be applied, the cost, and the consistency with other public land management objectives.

One other category of practices that is implicitly captured in FASOMGHG but is not broken out separately is riparian buffer establishment. As indicated above, riparian buffers are the establishment of vegetative cover such as grass or trees near water bodies. The model captures afforestation and grassland conversion, but it does not have the data to determine whether those conversions are taking place in riparian areas. Therefore, the model will implicitly capture establishment of trees and grasses in this area in response to the GHG incentives put forth (e.g., GHG price payments), but it will not be able to identify this distinctly as riparian buffers. As a result, the model cannot currently examine policies specifically aimed to increase riparian buffers.

Baseline GHG Projections from the Forest and Agriculture Sectors

The estimation of a baseline is an important first analytic step for this study, because the analyses of GHG mitigation potential presented in subsequent chapters must be measured against a credible baseline reflecting a continuation of BAU activity.

The analysis begins by using the FASOMGHG model to simulate future economic activity and corresponding GHG effects in the forest and agriculture sectors under a continuation of the status quo, or BAU. Departures from this baseline constitute the mitigation quantities estimated in response to the price and policy scenarios analyzed throughout this report.

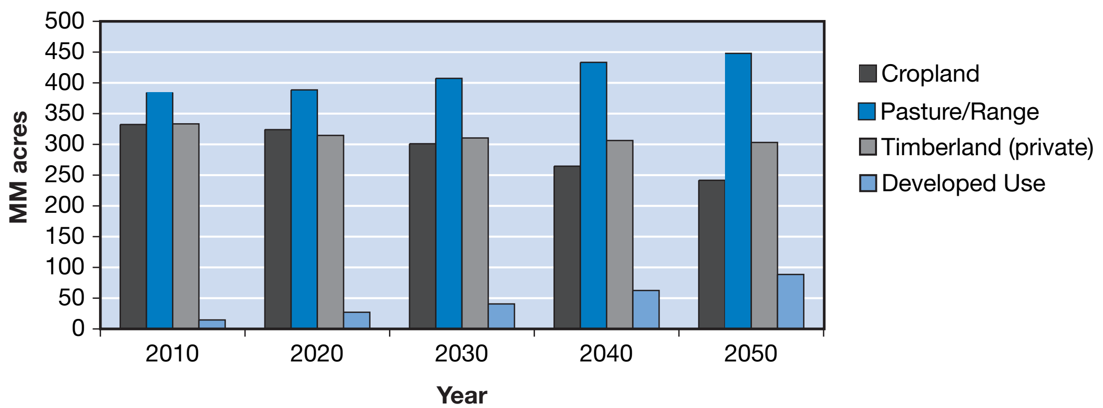
FASOMGHG Baseline Projections

This section presents baseline projections from the FASOMGHG model. These results reflect model outputs when FASOMGHG is run based on the exogenous data and trends discussed above and without any GHG policies in place. We look first at projections of key land-use and management trends and see how these comport with trends reported in recent land-use inventory data. We then look at the FASOMGHG projections of the sectors' GHG flows (emissions and sequestrations) and compare these projections with other secondary sources as well.

Baseline Land-Use and Management Projections

One of the driving factors of the GHG effects in these sectors is how land is expected to be used over time. FASOMGHG simulates land allocation for each region across time. National-level projection of land use across the major categories of cropland, pasture/range, timberland, and developed use is illustrated in Figure 3-4. Cropland is projected to decline steadily into the future as productivity improvements reduce the demand for cropland relative to other uses. This is a continuation of recent history, as discussed below. Pasture/range land is projected to rise over time, as demand for livestock products is projected to grow. Timberland is projected to decline just modestly over time, as demand for timber attracts some land from agriculture, but losses of land to developed use occurs.[10] Developed use is projected to grow substantially over time, attracting land from both forestry and agriculture and thereby reducing, to some extent, the capacity of the forest and agriculture sectors to mitigate GHGs through actions on the land base.

Figure 3 4: Baseline Land Use Projections, FASOMGHG: 2010 2050 (Million acres)



[10] The FASOMGHG projections for timberland out to 2050 are lower than those projected by the USDA Forest Service in their most recent RPA projection (USDA Forest Service 2003, Ch. 2, Table 5) primarily because of differences in coverage—the latter includes all 50 states, while the former includes the 48 contiguous states only. However, FASOMGHG projects a 9 percent loss of timberland between 2010 and 2050, while the USDA Forest Service projects a 4 percent loss of timberland. The economic forces captured by FASOMGHG suggest a more fluid change in land use than the USDA Forest Service methods.

As indicated above, FASOMGHG projections for declining cropland are consistent with recent trends observed in the United States. Table 3-7 reports data from the NRI, which tracks land-use change across major categories from 1982 to 1997. The biggest single change was in the area of cropland—a net loss of about 44 million acres (10.4 percent of the 1982 total). NRI data (not shown in the table) indicate that three-quarters of the 1982 to 1997 cropland loss total was diverted to CRP lands (about 33 million acres); the remaining lost cropland is net transfers to pasture and range, forestland, developed, and other uses. The CRP was established to remove cropland from production that is highly susceptible to erosion or otherwise unproductive. In the scenarios throughout this report, CRP land is assumed to remain permanently at the initial level of 33 million acres.

Factors Underlying Land-Use Change Trends

For private lands in a market economy, land-use decisions generally reflect each landowner's desire to maximize the utility obtained from his or her land by trying to maximize land profits (also called land "rents"). These landowners may be very responsive to changes in commodity output prices and input prices and make land management decisions to change the products they produce and the inputs they use as prices vary. Other landowners may place more emphasis on the nonmarket services provided by their land such as rural lifestyles, or wildlife habitat, more than maximizing the land's net income (Birch and Moulton 1997). These landowners may be less responsive to constantly changing market signals than more profit-oriented landowners. Over time these market signals—including GHG market price signals addressed in this report—may affect the landowner's land-use decisions under changing market and nonmarket conditions. Farmers may adopt conservation tillage practices, establish buffers along riparian corridors, and retire unproductive lands independent of, or in response to, market incentives for GHG mitigation.

Price trends in forestry and agricultural commodities or technological advances in equipment and land management options may be the largest factors influencing land-use change for rent-driven landowners. Figure 3-5 plots estimates of total

Table 3-7: U.S. Land-Use Change for Major Categories: 1982–1997

	Million Acres			
Land Cover/Use	1982	1997	Change	Percent
Cropland	420.6	376.7	–43.9	–10.4%
Conservation Reserve Program (CRP)	0.0	32.7	32.7	—
Pasture	131.9	119.9	–12.0	–9.1%
Rangeland	416.4	405.7	–10.8	–2.6%
Forestland[a]	403.0	406.6	3.6	0.9%
Other rural land	49.6	51.1	1.5	3.0%
Developed land	73.2	98.2	25.0	34.1%
Water areas and federal land	447.9	451.8	3.9	0.9%
Total	1,942.6	1,942.6	0.0	—

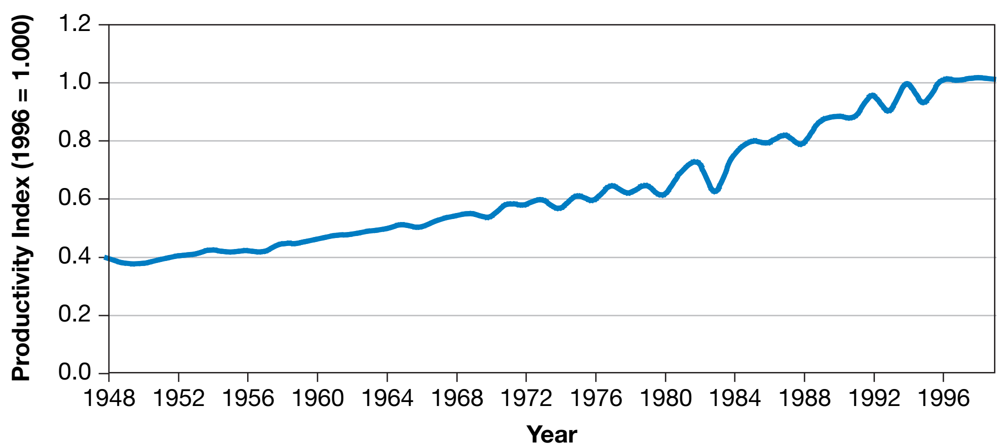
Source: USDA NRCS (2000).

[a] Forestland tracked by USDA, NRCS encompasses all productive timberland, as defined by USDA Forest Service, and reported in Table 3-6, plus forestland that is not considered productive enough to be timberland.

factor productivity in U.S. agriculture over the last half of the twentieth century,[11] averaging 1.8 percent per year. However, from 1979 to 1999, the average annual increase in productivity was about 2.3 percent.

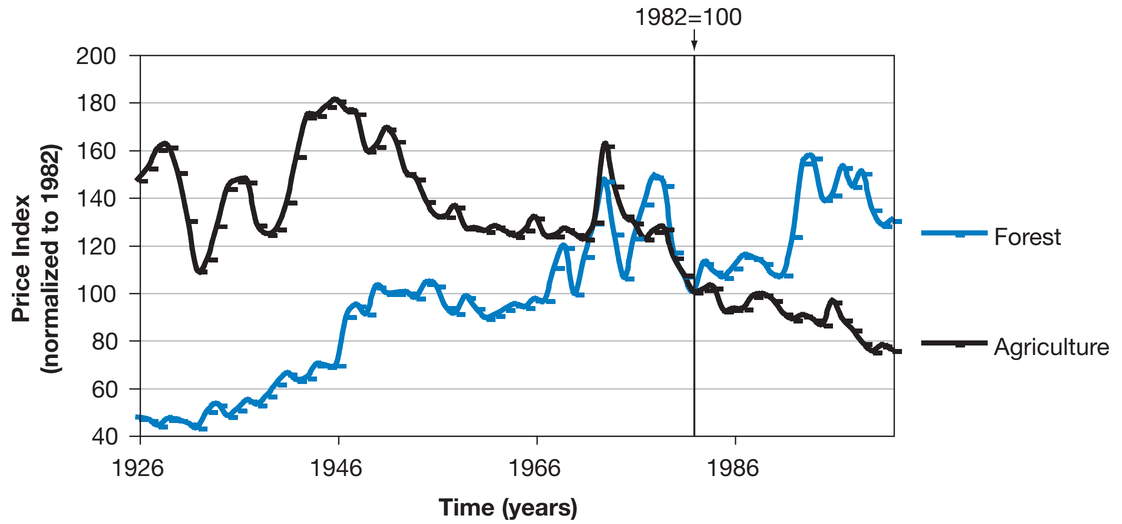
During this period, real agricultural prices (i.e., net of inflation) have trended downward; net farm income has stayed about even; and, as discussed above, land devoted to agriculture has dropped. Increases in agricultural productivity have reduced the amount of land needed for agriculture, leading to land retirement (CRP) and movement to pasture/range, timberland, or developed uses. As shown in Figure 3-6, the rise in forest-sector prices relative to agricultural prices provides incentive for that movement of land, along with increases in population and real income.

Figure 3 5: Total Factor Productivity in U.S. Agriculture: 1949 1998



Source: Ball, Butault, and Nehring (2001).
Data for figure downloaded from http://www.ers.usda.gov/data/agproductivity/.

Figure 3 6: Forest and Agriculture Products Price Series



Source: U.S. Department of Labor, Bureau of Labor Statistics (Annual Series).

[11] Total factor productivity measures the relative change in the ratio of total output produced to all inputs used. It is a comprehensive measure of productivity and is a standard measure of technical efficiency in production.

Another significant driver of land-use change is population growth. Population grew about 24 percent in the United States between 1980 and 2000 (Hobbs and Stoops 2002). Table 3-7 provides evidence of population's effect on land use: developed land uses experienced the highest increase between 1982 and 1997, with 25 million acres of land undergoing development during that time period, an increase of more than one-third.

Baseline GHG Projections

Table 3-8 presents the FASOMGHG baseline projection of net GHG emissions from the U.S. forest and agriculture sectors for decades 2010 to 2050 by specific activity group. The table reveals that the sectors host a unique mix of activities. Some activities, on balance, remove more GHGs from the atmosphere than they emit (e.g., forest carbon and, in some cases, agricultural soil carbon sequestration). Some are pure emission sources (e.g., CO_2 emissions from fossil fuel use, agricultural CH_4 and N_2O emissions). A small amount of baseline biofuel (biomass) offsets is expected to be generated in the form of ethanol substitution for liquid fuels. The net atmospheric GHG effect is negative (GHG removal), because these renewable biofuels replace the burning of fossil fuels.

To summarize, the most important baseline sectoral GHG effects over time are the following:

- The private forest sector is a net carbon sink, absorbing more CO_2 than it releases through harvests and land-use change. The sink effect, though, is projected to diminish in magnitude over time, from 436 Tg CO_2 per year in 2010 to 170 Tg CO_2 per year in 2050. In the baseline, there is some afforestation taking place in the

Table 3-8: Baseline Forest and Agriculture GHG Net Annual Emissions by Activity and Decade for the United States: FASOMGHG Model: 2010–2050

	2010	2020	2030	2040	2050
Forest-sector (private) sources/sinks[a]	**(436)**	**(222)**	**(145)**	**(225)**	**(170)**
Afforestation	(114)	92	18	4	26
Forest management	(322)	(314)	(163)	(229)	(196)
Agriculture-sector sources/sinks (direct)[b]	**521**	**513**	**477**	**449**	**459**
Agricultural soil carbon sequestration	32	10	(83)	(148)	(167)
Agricultural CH_4 and N_2O	489	503	560	597	626
Sources/sinks from agriculture-energy sector linkages[c]	**186**	**189**	**202**	**218**	**231**
Fossil fuel from crop production	197	200	213	229	242
Biofuel offsets	(11)	(11)	(11)	(11)	(11)
Combined forest- and agriculture-sector net GHG emissions[d]	**270**	**479**	**535**	**442**	**520**

[a] Sum of afforestation and forest management.

[b] Sum of agricultural soil carbon sequestration and agriculture CH_4 and N_2O.

[c] Sum of fossil fuel from crop production and biofuel offsets.

[d] Sum of three categories above.

Notes: All quantities are in Tg CO_2 Eq. per year. Negative (parenthesized) values are removals from the atmosphere (sinks). Positive (nonparenthesized) values are emissions to the atmosphere (sources); decade means annual average value for that decade. Some rounding error may occur.

first decade but not beyond that. Consequently, future decades show losses in carbon accumulated since the base year because of harvesting of the afforested lands.[12]

- Net "direct" agricultural GHG emissions—the sum of agricultural non-CO_2 emissions and soil carbon sequestration—exceed 500 Tg CO_2 per year in the baseline's first decade but eventually decline. Non-CO_2 emissions are projected to rise steadily throughout the projection period, but this rise in emissions is expected to be offset by soil carbon sequestration, which starts as a source but becomes a sink in later years. By 2050, agricultural soil carbon sequestration draws even with forest carbon sequestration at about 170 Tg CO_2 per year.
- Net emissions from agriculture attributable to energy production include CO_2 emissions from fossil fuel use in agricultural inputs offset by biofuel production in agriculture. Together, these factors are projected to account for 186 Tg net CO_2 per year in the 2010 decade, rising to about 230 Tg CO_2 per year in the 2050 decade, a gain of about 25 percent.
- Combining all direct and indirect sources and sinks in the combined forest and agriculture sectors, the model baseline is somewhat variable over time. The substantial drop in baseline forest carbon sequestration over the first 2 decades causes a substantial increase in the combined forest- and agriculture-sector net GHG baseline emissions, essentially doubling between 2010 and 2030 (270 to 535 Tg CO_2 per year). This GHG build-up reverses direction after 2030, as carbon sequestration from both forests and agricultural soils overtakes the rise in sector GHG emissions.

Comparison of FASOMGHG Baseline GHG Projection to Other Published Estimates

Several estimates exist of historic and projected GHG trends in U.S. forestry and agriculture, including those reported by EPA, USDA Forest Service, and others. We review these estimates here and compare them to the baseline used in the FASOMGHG model.

Forest Carbon Sequestration

For forest carbon, we rely on two principal baseline studies that have estimated past, current, and projected carbon sequestration rates of American forests:

- U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 – 2003* (EPA 2005)
- USDA Forest Service, *Carbon Sequestration in Wood and Paper Products* (Skog and Nicholson 2000)

EPA GHG Inventory Baseline. The national GHG inventory (EPA 2005) reports GHG emissions and sinks in the United States since 1990. Table 3-9 shows the net flux in CO_2 equivalents resulting from forestry activities, including the amount of carbon stored in harvested wood products. This combined forest + wood products measure is the most directly comparable to the FASOMGHG forest carbon measure. Together, the forest carbon sink components account for over 90 percent of all terrestrial carbon sequestration in the inventory; the remaining portion comes from agricultural soil carbon. Carbon contained in wood products constitutes about one-quarter to one-third of the total forest carbon sequestration total.

The total forest carbon flux reported in the EPA inventory declined steadily from 1990 to 2000. In 1990, the sector generated a net sink of nearly 950 Tg CO_2 Eq. per year, but this declined by about 200 Tg per year by 2000. Two-thirds (137 Tg CO_2 Eq. per year) of the decline in sequestration from 1990 to 2000 is attributable to a change in the methods used to estimate SOC between the two periods. The remaining third (64 Tg) is attributable to a reduced rate of afforestation, which was quite high in the late 1980s and early 1990s partly because of public conservation programs such as the CRP.

[12] The base year for these simulations is 2000. Model results are reported for the period 2010 to 2050 (see Chapter 4). Some of the carbon losses from "afforestation" are based on lands afforested in the 2000 decade.

Table 3-9: Net Annual CO_2 Flux from U.S. Forest Carbon Stocks: 1990 and 2000, EPA Inventory Quantities (in Tg CO_2 per year)[a]

Component	1990	2000
Forest	(739)	(537)
Above ground	(396)	(400)
Below ground	(77)	(78)
Dead wood	(74)	(45)
Litter	(67)	(26)
Soil organic carbon (SOC)[b]	(125)	12
Harvested wood	(210)	(211)
Wood products	(48)	(59)
Landfilled wood	(162)	(152)
Total net annual flux	(949)	(748)
Difference in net flux: 2000 vs. 1990		201
Difference, net of SOC		64

Source: EPA (2005).

[a] Negative (parenthesized) values are removals from the atmosphere (sinks). Positive (nonparenthesized) values are emissions to the atmosphere (sources).

[b] SOC differences are primarily due to changes in estimation methods.

USDA Forest Service Forest-Sector Baseline. The estimates in the EPA inventory report recent historical trends since 1990, but future projections are necessary for comparison against the FASOMGHG baseline. EPA estimates for the forest sector were derived collaboratively with the USDA Forest Service, using USDA Forest Service models referenced above (e.g., FORCARB). Therefore, we turn to a recent study by USDA Forest Service researchers that estimates national levels of forest carbon sequestration into the future to provide a consistent framework for comparison.

In 2000, the USDA Forest Service produced a comprehensive assessment of national forest carbon stocks and flows. Within that report, a chapter by Skog and Nicholson (2000) presents a set of projections for the period 1990 to 2040 that can be matched to the forest carbon categories reported by EPA above. The USDA Forest Service projections are presented in Table 3-10. According to those estimates, U.S. forest carbon sequestration exceeded 1.2 Gt CO_2 per year in 1990, at which point a steady decline is projected to extend but taper off through the middle of the 21st century. The forest sink is projected to decline about 360 Tg CO_2 per year (30 percent) from 1990 to 2040. But virtually all of that decline is found in the 1990 to 2000 decade, mirroring the drop reported in the EPA GHG inventory for that same time period. The projected annual decline in forest carbon sequestration from 2000 to 2040 is just 5 percent.

Table 3-10: Projected Net CO_2 Flux from U.S. Forest Carbon Stocks: 1990–2040, USDA Forest Service Estimate

	Net CO_2 Flux (Tg CO_2 per year)					
	1990	2000	2010	2020	2030	2040
Change in forest carbon stocks	1,006	694	705	646	609	591
Changes in harvested wood carbon stocks	218	211	235	250	261	270
Change in products in use	96	92	90	94	89	84
Change in landfills	123	119	145	156	172	186
Total change in stock of carbon	1,224	905	939	896	870	861

Source: Table 5.7 in Skog and Nicholson (2000).

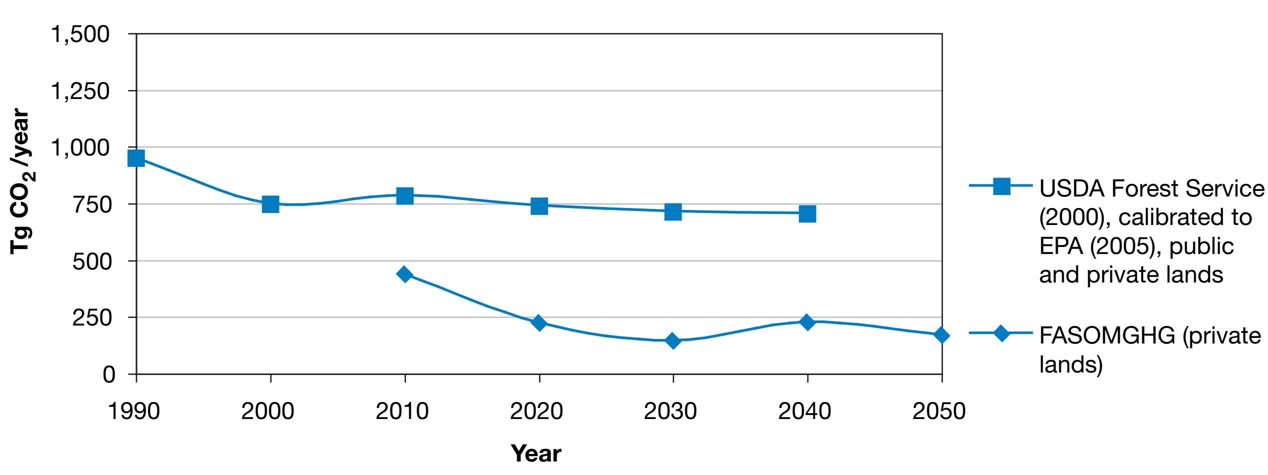
Comparison of Baseline Projections: USDA Forest Service and FASOMGHG. We now compare FASOMGHG's forest carbon baseline projections with projections for the corresponding time period by USDA Forest Service (Skog and Nicholson 2000). The comparison is illustrated in Figure 3-7.

Before proceeding with the comparison, we note several important points. First, the projection time periods do not exactly match: the USDA Forest Service projections run from 1990 to 2040, and FASOMGHG's projections run from 2010 to 2050. Therefore, the most meaningful comparisons are from 2010 to 2040. Second, in Tables 3-9 and 3-10 note the difference in the quantities between the EPA and USDA Forest Service estimates for 1990 and 2000. The 2000 value reported in the USDA Forest Service report is more than 150 Tg CO_2 higher than the EPA inventory estimate. Much of this difference is due to the methods-based adjustment in soil carbon estimates between 1990 and 2000 that is reflected in the EPA (2005) estimate but not in the Skog and Nicholson (2000) estimate. Because this soil adjustment is methodological in nature, we recalibrated the Skog and Nicholson projections to be more consistent with the EPA projection using the revised methodology. We did that by adjusting the USDA Forest Service projection downward to match the EPA estimate for 2000 (748 Tg CO_2) and then allowing the USDA Forest Service projection for 2000 to 2040 to pertain beyond that.

Third, the USDA Forest Service projections are for *all* forestland in the United States (private and public), while the FASOMGHG projections are for *private* land only. Although the inventory data for public forestland are somewhat incomplete, these forests are estimated to provide a substantial net carbon sink in the United States (Heath 2000). That essentially explains the large gap between the FASOMGHG and USDA Forest Service lines in Figure 3-7.

Putting aside the public lands gap in Figure 3-7, both sets of projections show a similar pattern, namely that the forest carbon sink is projected to decline over time. The decline is a bit more pronounced in FASOMGHG, reflecting differences in the methods used to create the projections. FASOMGHG uses economic principles and dynamic optimization methods to allocate resources across time, while the system used by Skog and Nicholson is not as explicitly driven by economic models of intertemporal economic behavior. However, both sets of projections are consistent in their assessment that under BAU

Figure 3 7: Comparison of Projected Baseline Carbon Sequestration Trends in U.S. Forests: FASOMGHG vs. USDA Forest Service Model



conditions, the rate of CO_2 sequestration in U.S. forest ecosystems is slated to decline over time. Therefore, absent any policy interventions or unforeseen changes in natural, economic, or institutional phenomena, the forest sector's role in partly offsetting the country's GHG emissions will diminish.

To summarize, forests make up the lion's share of current terrestrial sequestration in the United States and are a net sink because the amount of CO_2 currently taken up through photosynthesis and stored in biomass, soils, and products exceeds the amount released through harvesting and natural disturbances. This is the result of recent land-use trends, which show a net movement of land from agriculture to forests, and an age class structure of U.S. forests favoring younger, faster-growing trees. However, under BAU, these land-use conversions are not expected to occur at the same rate. Additionally, timberland is projected to be diverted to developed uses over the projection period, thereby leading to forest carbon losses. Taking these factors together, future sequestration rates in the U.S. forest sector are expected to decline below the rates we are now experiencing in the absence of additional forest carbon sequestration activities.

Agricultural Soil Carbon Sequestration

As was shown in Table 3-8, FASOMGHG projects agricultural soil as a net emitter of CO_2 in the early periods (about 30 Tg CO_2 in 2010) and as a significant sink in later years (nearly –170 Tg CO_2 in 2050), thereby tipping the sector's carbon balance toward sequestration by about 200 Tg CO_2 during this time period.

Although there are no published projections of future baseline agricultural soil carbon sequestration to compare with the FASOMGHG projections for 2010 to 2050, one can compare the 2010 projection—a small source of +32 Tg CO_2/year—with the most recent estimate (for data year 2003) reported in the U.S. GHG inventory (EPA 2005)—a small sink of –7 Tg CO_2/year. This gap reflects a difference between methods used in FASOMGHG (i.e., CENTURY model) and methods used in the EPA inventory (IPCC default factors with U.S. data), and assumptions on short-run baseline adoption of practices to sequester agricultural soil carbon. The FASOMGHG model reveals a pattern of low adoption of sequestration practices (predominately reduced tillage) in the early years of the projection but robust adoption in later years in response to projected changes in the underlying market and technological conditions. The EPA inventory estimates may reflect some adoption occurring sooner than projected in the FASOMGHG model. Other differences in underlying phenomena involving soil sequestration also may be occurring, such as the rate of cropland conversion to grassland and changes in nontillage soil management, including the addition of manure amendments.

Non-CO_2 GHG Emissions in Agriculture

According to the national GHG inventory report (EPA 2005), agricultural practices directly account for about 6 percent of all GHG emissions in the United States, primarily in the form of CH_4 and N_2O. These non-CO_2 GHG emissions from agriculture totaled about 433 Tg CO_2 Eq. in 2003 (see Table 3-11). As discussed earlier in this report, the primary sources of these GHGs in agriculture are fertilizer applications on croplands, enteric fermentation, manure management, and rice cultivation. Residue burning is also a small source of non-CO_2 gas emissions from agriculture. According to the national GHG inventory report, agriculture accounted for about 30 percent of all CH_4 emissions and 72 percent of all N_2O emissions in the United States.

Table 3-11 presents recent levels of agriculture non-CO_2 GHG emissions. The trends presented in Table 3-11 show a fairly slight (1.6 percent) increase in sector emissions between 1990 and 2003. Although they have increased, agricultural emissions have done so at a slower rate than total U.S. GHG emissions (EPA 2005).

Although the EPA inventory estimates are historic, a recent paper by Scheehle and Kruger (in press) provides projections for non-CO_2 GHG emissions out to 2020. Those projections are compared to the FASOMGHG projections in Figure 3-8 and are found to match rather well. The magnitudes of the estimates are within 5 percent of each other and both show a rising trend in non-CO_2 emissions over the next several decades.

Sources/Sinks from Agriculture-Energy Linkages

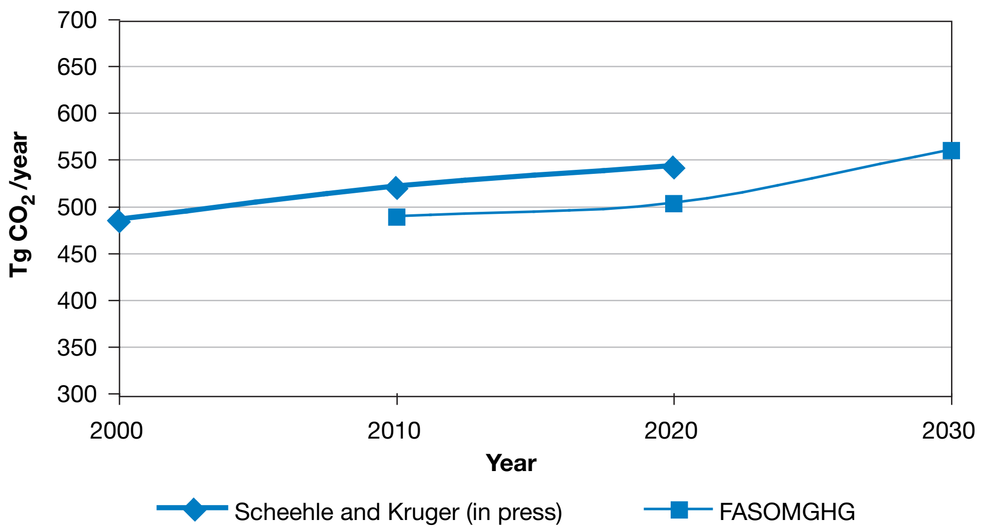
As reported in Table 3-8, a sizeable portion of the sector's total emissions originate from CO_2 released in fossil fuel combustion embodied in the energy to produce agricultural inputs. As described above, this not only includes on-farm use of fuels in farm machinery, but also the upstream energy use in the production of inputs, such as the amount of energy used to produce fertilizer. This is a more expansive definition of agricultural CO_2 emissions than others have employed and therefore there are no direct

Table 3-11: Non-CO_2 GHG Emissions from Agriculture (Tg CO_2 Eq.): EPA GHG Inventory, 1990–2003

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**156.9**	**163.0**	**164.2**	**164.6**	**162.0**	**161.9**	**161.5**	**161.8**
Enteric fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Manure management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Rice cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Agricultural residue burning	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
N_2O	**269.6**	**269.8**	**285.6**	**261.3**	**282.1**	**275.6**	**270.9**	**271.5**
Agricultural soil management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Manure management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Agricultural residue burning	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4
Non-CO_2 GHG Emissions Total	**426.5**	**432.8**	**449.8**	**425.9**	**444.1**	**437.5**	**432.4**	**433.3**

Note: Totals may not sum due to independent rounding.
Source: These numbers are taken from EPA (2005).

Figure 3 8: Comparison of Projected Baseline Non CO$_2$ GHG: FASOMGHG vs. Scheehle and Kruger (in press)



comparisons that can be made to the FASOMGHG estimate. The closest comparison one can make is to the 2005 EPA GHG inventory, which shows CO_2 emissions from agricultural equipment of about 41 Tg CO_2 per year in 2003 (EPA 2005, Table 3-36 in Annex 3-2).

Applying FASOMGHG for the Purposes of this Report

FASOMGHG evaluates the joint economic and biophysical effects of GHG mitigation policies in the U.S. forest and agriculture sectors. The model considers most major GHG mitigation options and GHG flows in the two sectors over an extended time period. As an economic model, FASOMGHG ensures consideration of the effects of policy initiatives on resource flows and economic activities within and across the forest and agriculture sectors over time. It has sufficient detail to answer questions about which activities are economic, how much GHGs are reduced by their adoption, and where and when the actions are likely to occur. Interpretation of the model results can provide insights into how and why these activities and GHG effects occur.

FASOMGHG and its component models have been extensively peer reviewed.[14] The model is consistent with modern economic theory, agronomy, and ecology. FASOMGHG is empirically grounded with base period data (ca. 1990 to 2000) tied to published projections of key data and parameters for simulation of future scenarios.

The comprehensiveness, detail, theoretical consistency, and empirical grounding of FASOMGHG make it suited for policy analyses of GHG policies, including the introduction of GHG (sometimes called carbon or CO_2) prices, GHG quantity goals, and nuanced combinations thereof. Like any model, some abstraction of real-world complex details is necessary to make the problem tractable, which can hinder the flow of some information. Therefore, one may want to focus more on the broad and subtle patterns found in the model results and what they mean for GHG policy, rather than on specific estimates of a GHG or economic effect at a certain point in place and time.

[14] For a selected listing of publications using FASOMGHG and its predecessor models (ASM and FASOM), see http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers.htm.

CHAPTER 4

Mitigation Potential: Comprehensive Scenarios with All Activities and All GHGs

Chapter 4 Summary

Mitigation results are presented for all forest and agricultural activities and all GHGs under constant and rising GHG price scenarios over a range of \$1 to \$50 per t CO_2 Eq. (or roughly \$4 to \$184 per t C Eq.). Mitigation quantities are reported as changes from FASOMGHG's baseline. Low GHG price incentives have little effect on land-use change, but higher prices can induce substantial land-use change from agriculture to forestry and changes in practices within sectors. The price level affects the optimal portfolio of mitigation strategies. Carbon sequestration from agricultural soil practices and forest management dominates at lower GHG prices and in the near term. These two options produce about 90 percent of all mitigation in the earlier years, but these annual sequestration effects diminish by 2055. Afforestation dominates mitigation at higher prices in the early to middle years. However, carbon sequestered in afforestation is reversed by 2055, at which time the planted forests become a net CO_2 source. At the highest prices and in the later years, biofuels are a dominant strategy.

Timing effects vary depending on the GHG price scenario. In the constant-price scenarios, GHG mitigation declines over time, as landowners react early to incentives. Declining rates of mitigation are the result of carbon saturation (reaching a new equilibrium), harvests, and the conversion of forests back to agriculture. Despite these declining annual mitigation rates, cumulative mitigation steadily increases. In the rising-price scenarios, GHG mitigation increases over time as landowners are assumed to fully recognize that prices will rise and therefore employ some mitigation actions later. Mitigation potential has a regional distribution. The South-Central, Corn Belt, and Southeast regions possess the largest GHG mitigation potential, while the Rockies, Southwest, and Pacific Coast regions generate the least.

Chapter 3 describes the modeling framework of FASOMGHG and its projected baseline of GHG emissions and sinks in U.S. forestry and agriculture. This chapter presents FASOMGHG mitigation results as changes from the baseline, in terms of additional carbon sequestration and GHG reductions. Mitigation results are presented for a range of hypothetical scenarios that include both constant and rising economic incentives for GHG mitigation over time. More specifically, results from the GHG mitigation scenarios show management and land-use changes, average annual GHG mitigation for selected years (focusing on the next few decades), cumulative GHG mitigation over time, results by region, results by individual mitigation option, and a brief overview of key environmental co-effects. The emphasis here is on identifying and quantifying GHG mitigation opportunities at various economic values of GHGs, not on simulating a specific policy.

Mitigation Responses under Various GHG Mitigation Scenarios

This section estimates net GHG emissions from U.S. forestry and agriculture, reported as changes from the baseline levels, through a combination of sequestration and emission reduction strategies. The primary approach evaluated throughout this report is the assignment of a price for GHG emissions and sequestration. Under such pricing, landowners or other economic agents would receive payments for increasing sequestration and reducing emissions and would make payments for increasing emissions or reducing sequestration. The actual mechanism of providing GHG incentives and disincentives for participants specifically is not addressed here. The basic principle in the GHG price analyses below is that GHG prices provide incentives for increasing sequestration through land-use change, forest management, conservation tillage, and other forms of land management, and for decreasing emissions through land-use change (e.g., deforestation), harvesting, input use, and processes that generate non-CO_2 GHGs.

Varying the prices of GHGs in the FASOMGHG model of the forest and agriculture sectors allows for an evaluation of the total GHG mitigation potential from these sectors at different economic incentive (price) levels and identifies the activities and regions that comprise the most cost-effective portfolio of mitigation options. Proposing or designing specific climate mitigation policies for these sectors is beyond the scope of this report. Thus, the section continues with a description of hypothetical core price scenarios for GHG emissions and sequestration. This approach is consistent with numerous modeling efforts conducted in the recent past that have examined GHG mitigation responses across countries, time, and sectors to hypothetical GHG price scenarios.[1] Following the scenarios description, the section presents mitigation results from the FASOMGHG model. Variations on these core price scenarios are presented in subsequent chapters.

Boxes 4-1 and 4-2 detail reporting conventions used throughout the next few chapters with respect to measurement units and mitigation quantities across time periods.

Scenarios Description: Constant and Rising Incentives for GHG Mitigation

The mitigation analysis begins by stipulating a core set of scenarios that simulate the effects of setting a value for GHGs and modeling the subsequent effect on economic behavior and GHG emissions and sequestration.

Constant-Price Scenarios

The core price scenarios are described in Table 4-1 and are divided into two groups. The first group includes the constant-price scenarios, which evaluate GHG price levels ranging from \$1 to \$50 per tonne of CO_2 equivalent (t CO_2 Eq.) but assumes that the prices remain constant in real (inflation-adjusted) terms over time. Because many climate-modeling analyses use carbon (C), rather than CO_2, as the unit of measure, Table 4-2 presents the carbon price equivalent to the CO_2 prices. The purpose of evaluating a range of GHG prices is to see not only how the total level of mitigation changes over the price range, but how the composition by activity and region changes as well.

Box 4-1: Measurement Units Reported in the Analysis

- The units of exchange for all GHGs are tonnes (t) of CO_2 equivalent (Eq.): 1 tonne (metric ton) = 1,000 kg = 1 Megagram (Mg) = 1.102 short tons = 2,205 lbs.
- CH_4 and N_2O are converted to CO_2 Eq. with GWPs from the IPCC (1996) Second Assessment Report (see Box 1-1 in Chapter 1).
- Most mitigation results in this and subsequent chapters are given in teragrams (Tg) of CO_2 Eq. 1 Teragram = 1 million tonnes.

[1] For a sample of modeling efforts evaluating the effects of broad GHG incentive analyses, consult Web sites for the Stanford Energy Modeling Forum (EMF) (http://www.stanford. edu/group/EMF/publications/index.htm), the MIT Joint Program on the Science and Policy of Climate Change (http://web.mit.edu/globalchange/www/reports.html), and The Pew Center for Global Climate Change (http://www. pewclimate.org/policy_center/reports/) among others.

Box 4-2: Methods Used for Reporting GHG Mitigation Results at Different Points in Time

Annual averages: Present the average level of GHG reductions represented in FASOMGHG for a given year. For the purposes of this report, the annual values for 3 specific years—2015, 2025, and 2055—are used to represent results in the short, intermediate, and long runs. These years represent the midpoint of the decades 2010, 2020, and 2050 tracked in the model and are annual averages for the decades.

Cumulative: Reports results as the cumulative GHG mitigated over the full projection period or period specified. This value is the amount of GHG mitigated in year n plus the total amount mitigated in year (n – 1) + (n – 2) + (n – 3) ... back to the beginning year of the simulation (2010). Although specific options may increase emissions compared to the baseline, the cumulative effect may still be a net GHG reduction as a result of the reductions from the full suite of mitigation options.

Annualized quantities: Because mitigation effects can vary tremendously over time, a concise summary metric is needed to convey the GHG mitigation potential over a given time period. The metric used for these purposes in this report is the annualized equivalent value GHG mitigation quantity. The annualized equivalent refers to the equivalency between the *net present value* of all GHG mitigation over a given projection period (typically the full horizon, 2010 to 2110, but shorter time horizons can be considered)—accounting for variable GHG gains and losses over time—and receiving a fixed quantity of GHG mitigation each year for the same projection period. By using net present value concepts, the annual GHG effects are time discounted; therefore, near-term effects are weighted more heavily than those in later time periods. (The rationale for such an approach is discussed in Herzog et al. [2003].) The discount rate used is 4 percent per year. More information on this metric is provided in Box 4-5.

Table 4-1: Core Price Scenarios

	Initial Price in 2010 ($/t CO_2 Eq.)	Annual Price Growth	Price Cap
Constant Prices			
	$1	0	None
	$5	0	None
	$15	0	None
	$30	0	None
	$50	0	None
Rising Prices			
	$3	1.5%/yr	None
	$3	4%/yr	$30
	$20	$1.30/yr	$75

Table 4-2: CO_2 and C Price Equivalents

CO_2 Price ($ per t CO_2 Eq.)	C Price ($ per t C Eq.)
$1	$3.67
$3	$11.01
$5	$18.35
$15	$55.05
$20	$73.40
$30	$110.10
$50	$183.50
$75	$275.25

Note: One unit of C equates to 3.67 units of CO_2.

Rising-Price Scenarios

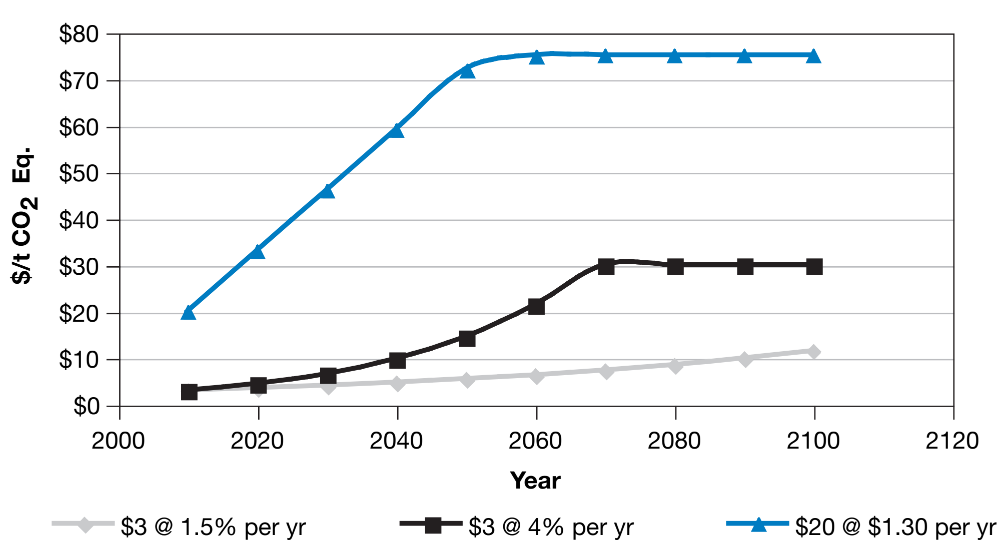
The second group of scenarios in Table 4-1 addresses rising GHG prices, wherein an initial price is asserted beginning in Year 2010, as well as a rate of increase over time. These scenarios provide a means to examine whether the incentive for delayed action to capture mitigation at higher future prices is quantitatively important in these sectors. Figure 4-1 shows the price trajectories associated with each of the three rising-price scenarios, illuminating the differences in the rate of increase and price levels attained.

The first two rising-price scenarios have a modest initial price of \$3/t CO_2 Eq., rising alternatively at 1.5 and 4 percent per annum over the time period. The price caps out at \$30/t CO_2 Eq. under the 4 percent price rise scenario. The third scenario commences at a price of \$20/t CO_2 Eq., rising at \$1.30 per year, capping out at a price of \$75. This third price scenario roughly matches a fairly aggressive price path considered by modeling efforts tied to the Stanford University EMF (http://www.stanford.edu/group/ EMF/home/index.htm). Price caps are introduced to keep carbon prices from reaching seemingly unrealistic levels and are in accordance with other scenarios tested in past research. For further discussion of rising price scenarios, see van't Veld and Plantinga (2005).

The model is initially run to reflect comprehensive coverage. Comprehensive means that all forestry and agricultural activities and all GHGs (CO_2, CH_4, N_2O) represented in FASOMGHG are subject to the GHG payment scenarios. These results, in essence, help identify the *competitive potential* of individual mitigation options and of the aggregate U.S. forest and agriculture sectors for GHG mitigation. See Box 4-3 for a description of technical, economic, and competitive potential as they relate to assessing GHG mitigation. Later, the report considers a more refined set of scenarios that are less comprehensive and more selective in coverage.

The FASOMGHG model is run in decadal time steps for the time period 2010 to 2110. Because there is greater uncertainty in model projections beyond the first several decades, the analysis results focus primarily on selected years: 2015, 2025, and 2055. Longer-term results are presented to highlight the unique temporal dynamics of carbon sequestration mitigation strategies in the forest and agriculture sectors. The following discussion focuses first on mitigation results for the constant-price scenarios and then turns to results for the rising-price scenarios.

Figure 4 1: Price Trajectories for Rising Price Scenarios



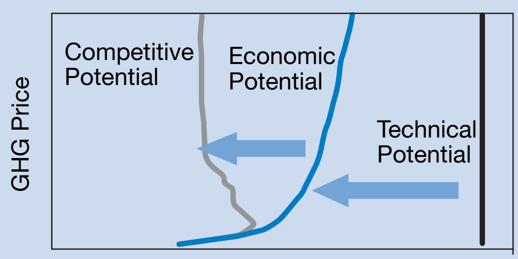
Mitigation Response to Constant GHG Price Scenarios

The mitigation responses to the constant GHG price scenarios are presented in the following order:

- land-use and land management effects,
- total national GHG mitigation quantities for selected years,
- total cumulative GHG mitigation over time,
- GHG mitigation by individual forestry and agricultural activities,
- GHG mitigation by region, and
- non-GHG environmental co-effects.

Box 4-3: Technical, Economic, and Competitive Potential of a GHG Mitigation Option

Example: U.S. agricultural soil carbon sequestration potential



Source: McCarl and Schneider (2001).

The *technical* potential reflects the maximum biophysical potential for GHG mitigation if all resources were committed to this objective without regard to cost. The *economic* potential incorporates the cost of mitigation options by showing that increasing levels of compensation are necessary to procure higher levels of GHG mitigation from the activity. The economic potential can fall well within the technical potential at price ranges considered in this analysis. Finally, the *competitive* potential reflects the interaction of the GHG mitigation activity with all other activity in the forest and agriculture sectors.

For example, while the economic potential shows that agricultural soil carbon sequestration becomes more profitable at higher prices, the competitive potential recognizes that other mitigation options within the sectors (such as afforestation and biofuels) also become more profitable at higher prices. Therefore, some of the economic potential for agricultural soil carbon sequestration is diverted to other more profitable options within forestry and agriculture at higher GHG prices.

A summary of the results that unfold under the constant-price scenarios is presented in Box 4-4.

Land-Use and Land Management Effects

The GHG price incentives alter the economic returns to land and can thereby affect the way that land is allocated across uses. Figure 4-2 illustrates this by showing differences in land use in Year 2025 simulated by variations in the GHG price.

The largest impact is on private timberland, which increases from 315 million acres (128 million ha) in the baseline ($0 price) to about 427 million acres (173 million ha) at the $50/t CO_2 Eq. price, reflecting the prominent role of afforestation in the higher price scenarios. The gain in timberland comes at the expense of losses in both cropland and pastureland. However, this gain in timberland may be temporary. As shown in Figure 4-3, the large increase in timberland at the beginning of the period brought about by a high GHG price ($50/t CO_2 Eq.) dissipates over time as the total

Box 4-4: Summary of Constant GHG Price Scenario Results

The mitigation responses to the constant GHG price scenarios are summarized here and presented in detail in the main text and in Table 4.A.1 in the appendix:

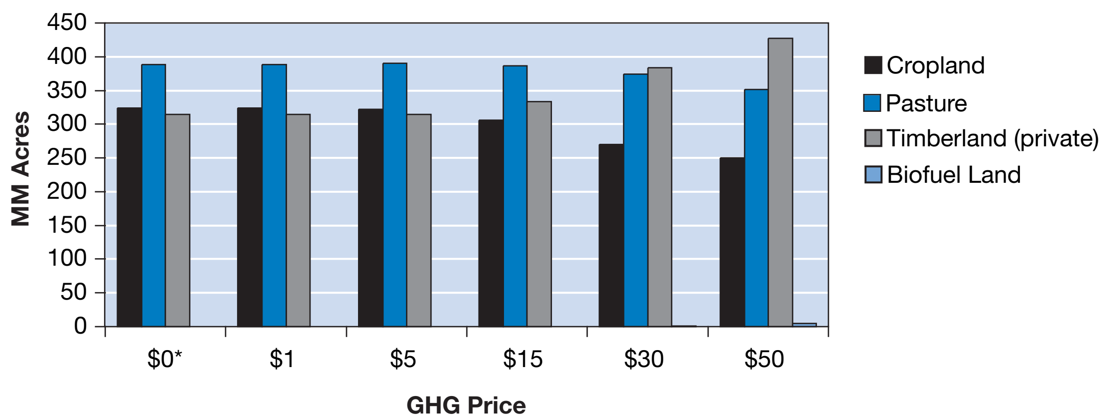
- The lower GHG prices have little effect on land-use change. Starting at the $15/t CO_2 Eq. (or $55/t C Eq.) price, however, appreciable effects on cropland (decline) and timberland (increase) start to materialize. It is not until the highest prices that pastureland begins to decline and biofuel lands increase.
- In the first decade, total national GHG mitigation is low at the low GHG prices—121 Tg CO_2 Eq./year (or 33 Tg C Eq.) at the $1 CO_2 price ($4/t C). This would offset about 2 percent of total national GHG emissions. However, under the highest price scenario ($50), 1,500 Tg CO_2, or over 21 percent of the current national GHG emissions total, could be mitigated.
- Forest management and soil carbon sequestration are dominant at the lower GHG prices. At a $5 CO_2 price, these activities account for 86 percent (260 Tg CO_2 Eq., or 71 Tg C Eq.) of total mitigation by 2015.
- Afforestation is the dominant mitigation activity at the higher GHG prices. At $50, 877 and 1,296 Tg CO_2 Eq. (or 239 and 353 Tg C Eq.) are mitigated by 2015 and 2025, respectively.

area of timberland reverts back to baseline levels after several decades. This reversion of lands to baseline conditions is driven by the fact that, at some point, the economic returns from converting lands back to agriculture are higher compared to keeping lands tied up in forestry. Moreover, there continue to be exogenous demands for land to be used for developed uses, which can divert land that otherwise may be allocated to forests. Thus, reversals occur in both land use and accumulated carbon benefits.

In addition to altering the allocation of land uses, GHG prices can also affect how land within a major use is managed. Table 4-3 shows the area of land converted from conventional crop tillage to reduced tillage under the baseline and GHG price scenarios over time.

In the baseline, FASOMGHG projects a fair amount of new reduced tillage by 2015—20 million acres (8 million ha)—and this amount grows over time to more than 30 million acres (12 million ha)

Figure 4 2: Land Use in 2025 at Different GHG Price Levels



*Baseline
Notes: $ represent price per tonne, CO_2 Eq.
Quantities are in million acres.

Figure 4 3: Timberland Area over Time: $50/t CO_2 Eq. vs. Baseline

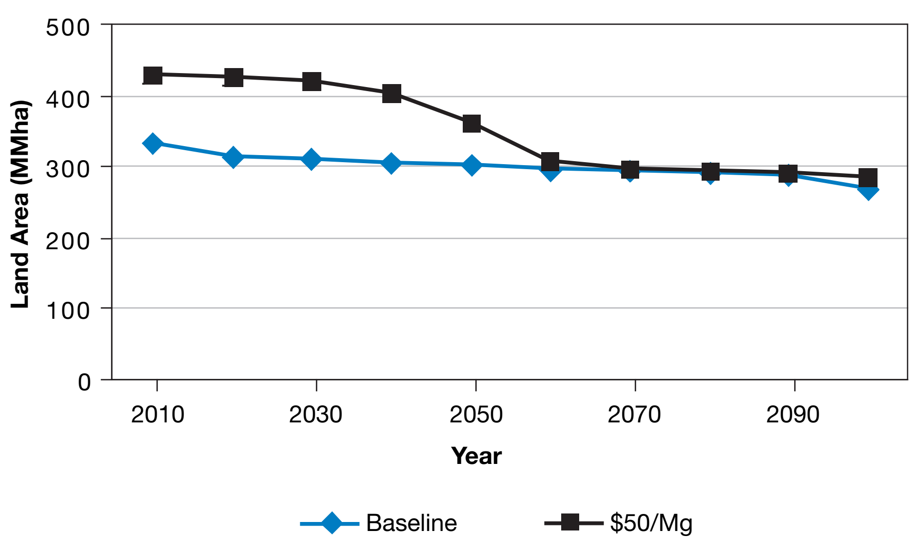


Table 4-3: Acreage Converted from Conventional Tillage to Reduced Tillage under Baseline and GHG Prices: U.S. Total (Million acres)

		GHG Price ($/t CO_2, constant over time)				
Year **From Conventional Tillage to . . .**	**Baseline**	**$1**	**$5**	**$15**	**$30**	**$50**
2015			Million Acres[a]			
Conservation tillage	10.5	48.5	31.4	2.1	0.4	0.6
Zero tillage	9.8	40.6	111.7	153.8	144.6	129.3
Total reduced tillage	20.4	89.2	143.1	155.9	145.0	129.9
2025						
Conservation tillage	20.3	6.4	0.3	0.0	0.1	0.1
Zero tillage	5.4	8.0	4.9	3.2	4.2	3.2
Total reduced tillage	25.7	14.4	5.3	3.2	4.2	3.3
2055						
Conservation tillage	27.5	6.1	0.1	6.2	0.0	0.0
Zero tillage	3.6	6.6	3.1	2.0	3.0	0.4
Total reduced tillage	31.0	12.7	3.2	8.2	3.0	0.4

[a] Baseline acres are the projection of tillage change under no GHG mitigation scenario. Acres for the GHG price scenarios are absolute values, rather than differences from the baseline (note: many other estimates in the report are the latter).

by 2055. However, the amount of cropland converted to reduced tillage rises dramatically under GHG pricing, ranging from about 90 to 155 million acres (36 to 63 million ha) by 2015. The latter number is almost half of the nation's cropland base. Most of this land goes into zero tillage ("no-till") practices. This is especially pronounced at the higher GHG prices, for which the extra financial gain from reducing tillage further is most pronounced. Note that the decline in tillage conversion after 2015 does not mean that reversion to conventional tillage is occurring. Rather, it means that there are fewer acres converting from conventional tillage to conservation or zero tillage at that time, primarily because most of these conversions have already occurred in previous periods.

However, note that the total reduced tillage acreage is highest at the $15 GHG price. Reduced tillage acreage is lower under the $30 and $50 prices because the amount of total cropland is projected to decline as land is diverted from crop production to forests and biofuels at the two higher prices, as shown in Figure 4-2. This relative decline in tillage adoption at the highest prices underscores the differences in economic and competitive potential referenced in Box 4-3.

The introduction of GHG prices also induces changes in forest management. Figure 4-4 illustrates the effects of different GHG prices on the average rotation (harvest) age of existing timber stands and the average management intensity of timber stands that are reforested after harvest. Chapter 2 discusses how GHG prices can extend harvest rotation ages; Figure 4-4 gives empirical evidence of this effect. Higher GHG prices tend to lengthen the rotation age, although the effect is not dramatic. The projected baseline (national) average rotation age is about 56 years for the 2015 period. This rises to about 62 years at a price of $50/t CO_2. Management intensity is indexed on a scale of 1 to 4; 4 is the most intensive form of forest management (e.g., site preparation, fertilization, thinning, prescribed burns), and 1 represents essentially no active management. Figure 4-4 shows that GHG prices raise management intensity because the additional management generates additional carbon.

Total National GHG Mitigation Quantities for Selected Years

Figure 4-5 presents total national results for the constant-price scenarios in terms of annual GHG mitigation achieved for the focal years 2015, 2025, and 2055. More detail on the contribution of specific activities to the national mitigation total for these key years can be found in Table 4.A.1 in the appendix to this chapter.

As expected, the total amount of GHGs mitigated by the forest and agriculture sectors rises with the size of the economic incentive. In 2015, annual mitigation totals for the forest and agriculture sectors range from fairly modest at the $1 price (121 Tg CO_2 Eq. per year) to substantial at the $50 price (about 1,500 Tg CO_2 per year). These quantities are, respectively, just under 2 percent and just under 22 percent of 2003 GHG emissions for the United States (EPA 2005), the latter of which could clearly be a substantial contribution to aggregate national mitigation potential, although at that price ($50/t CO_2 Eq. or $183.50/t C Eq.), mitigation options from other sectors could be substantial as well.

Note that the annual mitigation quantities rise between 2015 and 2025, particularly at the higher prices for which forest carbon sequestration from afforestation—which takes some time to culminate—plays a more significant role in the mitigation portfolio, as discussed below. The mitigation potential is generally lower in 2055 than in 2025 or 2015, reflecting the saturating and reversal effects of sequestration options referenced above. More discussion of the time element of mitigation options in these sectors now follows.

Figure 4 4: Effect of GHG Prices on Forest Management Variables, 2015

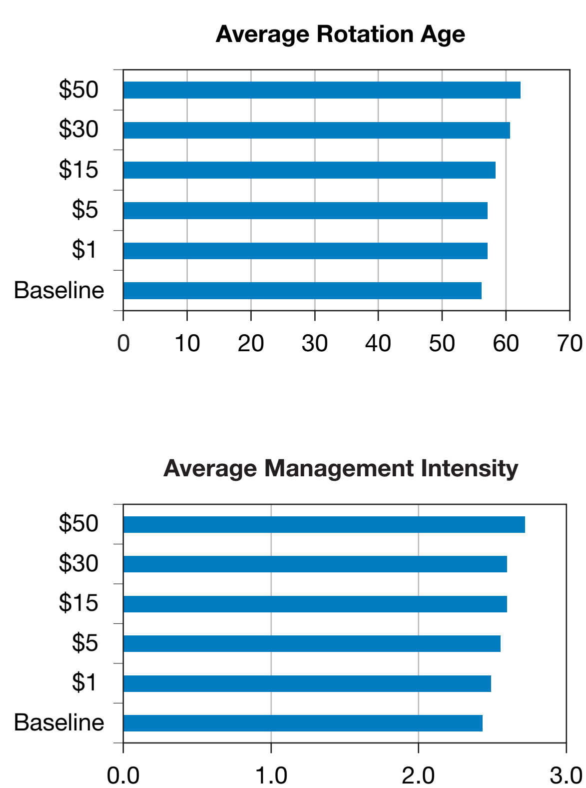
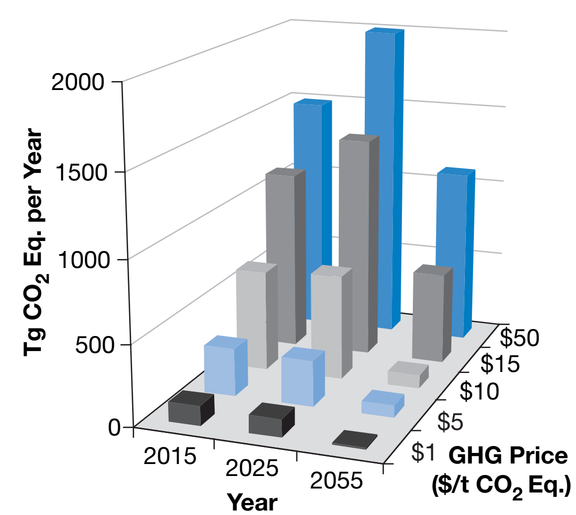


Figure 4 5: National GHG Mitigation at Representative Years by Price (2015, 2025, and 2055)

Quantities are in Tg CO_2 Eq. per year net emissions reduction below baseline.

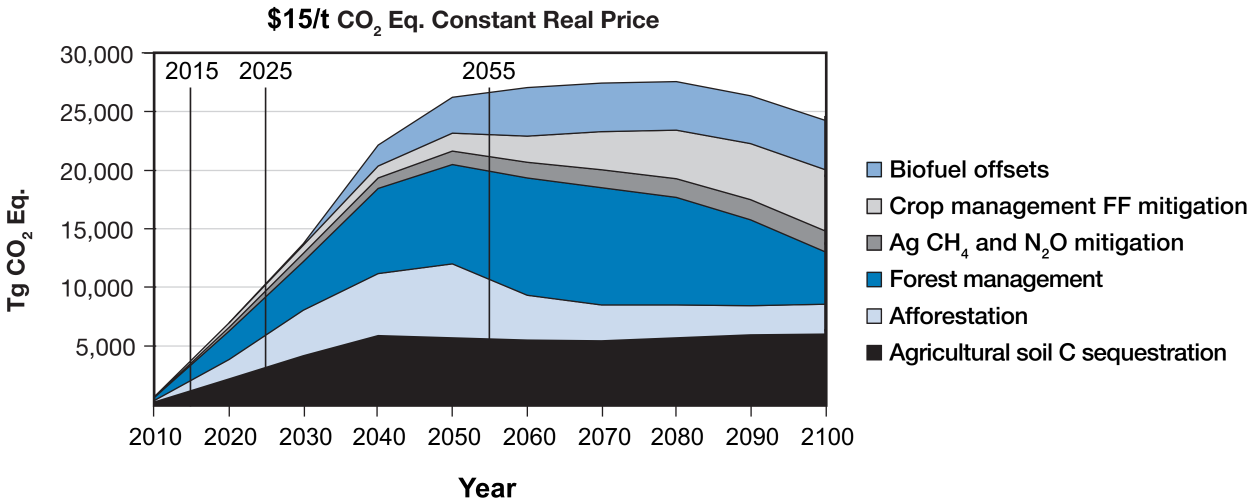


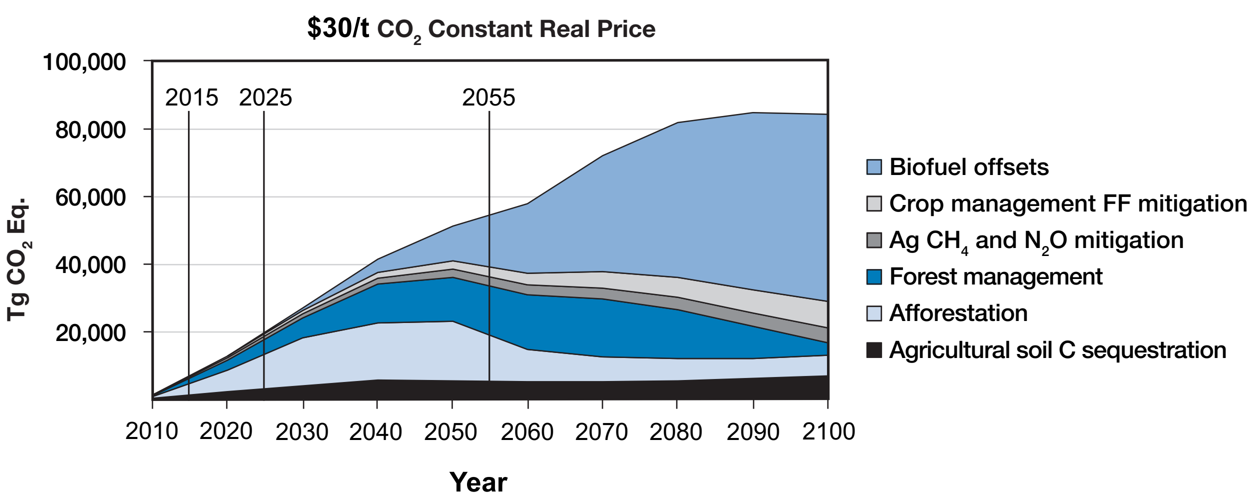
Total Cumulative GHG Mitigation Over Time

Given the unique dynamics of carbon sequestration, it is especially important to look at cumulative GHG mitigation results over time. In a given year, a specific mitigation option can produce an increase or reduction in GHG emissions relative to the baseline. Reporting the results annually may therefore hide the cumulative effect of the mitigation options over time. The long-term emission reductions and sequestration are more important than short-term fluctuations when addressing climate change issues.

Figure 4-6 shows cumulative GHG effects over the entire projection period for the $15 and $30 per t CO_2 Eq. constant price scenarios, respectively. After several decades, some reversal of carbon sequestration occurs as soil carbon equilibrium points are reached and carbon reversals occur through timber harvesting and reversion of afforested lands back to agriculture. Afforestation efforts early on in the period accumulate for several decades as the newly planted trees sequester carbon. Then, as the trees are harvested in the future, CO_2 is released again into the atmosphere, reversing some of the cumulative carbon built up

Figure 4 6: Cumulative GHG Mitigation over Time
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.





*Note differences in the quantity range on the vertical axis of each diagram.

over time. Cumulative agricultural soil carbon sequestration rises, then stabilizes after several decades as the carbon benefits of reduced tillage practices saturate. Forest management shows a saturating and slight reversal effect as well.

These patterns highlight an important difference between the duration of sequestration relative to other mitigation options within the forest and agriculture sectors. While the sequestration options display saturation and impermanence, the fossil fuel CO_2 and non-CO_2 emission reduction options essentially do not. The latter reductions are considered more permanent, because the avoidance of an emission does not create the same biophysical diminishing returns and risk of re-release as sequestration.[2] Differences between the cumulative contribution of sequestration and nonsequestration options widen over time and are particularly pronounced in the second part of the century and at the higher GHG prices.

GHG Mitigation by Individual Forestry and Agricultural Activities: Annualized Results

One way to summarize the net effects of the differing time dynamics is to determine a single measure of GHG effects over the entire simulation period 2010 to 2110. The measure employed here computes the annualized equivalent GHG quantity effect. By annualizing the estimates, one focuses more on comparing mitigation quantities across activities and regions and focuses less on comparisons across points in time. Box 4-5 describes how the annualization approach is applied to generate GHG mitigation estimates in this study.

[2] The analysis does not explicitly consider that avoiding CO_2 emissions from fossil fuel might also have some elements of impermanence as well. Avoided fossil fuel use simply retains the carbon stock below ground for possible release in the future. Although this is not as volatile and subject to rapid release as terrestrial carbon, there are some risks of impermanence nonetheless. Non-CO_2 emissions avoidance is somewhat less prone to the impermanence effect than CO_2 fossil fuel emissions.

Box 4-5: Annualizing Results over the Projection Period

One way to summarize the net effects of the differing time dynamics is to determine a single measure of GHG effects over the entire simulation period 2010 to 2110. By annualizing the estimates, one can focus more on broadly comparing mitigation quantities across scenarios, activities, and regions and focus less on comparisons across specific points in time.

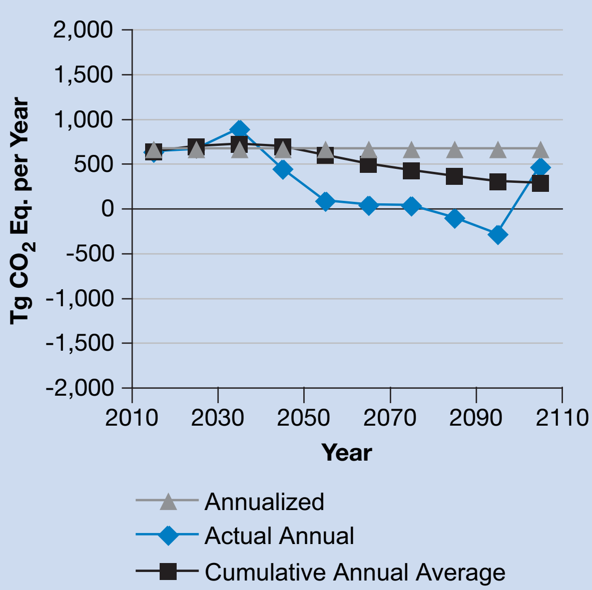
The annualized value provides a single measure that essentially “smoothes out” variability over time, while using the notion of time discounting to enhance the value of near-term mitigation over mitigation occurring in the distant future. Herzog et al. (2003) discuss the rationale for using time-discounting concepts to quantify physical mitigation quantities over time. Note that the annualization approach outlined here is appropriate only when GHG prices are constant over time. Therefore, only the constant-price scenarios in this report are reported using annualized estimates.

The annualized measure is computed by first taking the net present value of the GHG mitigation quantities over time: $NPV_G = \sum_{t=1}^{T} G_t/(1+r)^t$, where G_t is the GHG effect in time period (decade) t; T is the length of the simulation (in this case 100 years); and r is the annual discount rate, which is 4 percent for this analysis. The NPV_G value in the equation above is then annualized via the following calculation: $G_A = NPV_G * AF$, where AF is the annualization factor for converting a lump sum present value, such as NPV_G into its annualized equivalent. For a 100-year time period evaluated at a 4 percent discount rate, the AF is 0.0408. The formula for the annualization factor is $AF = r(1+r)^T / [(1+r)^T–1]$.

Figure 4-7 shows the effect of providing a single annualized value for a highly variable time trend such as the annual mitigation estimates for the \$15/t CO_2 Eq. price scenario. In the figure, the actual projected annual values vary from about +900 Tg CO_2 Eq. per year in the middle of the projection to –300 Tg CO_2 Eq. per year toward the end of the projection, reflecting the carbon reversal pattern discussed earlier in this chapter. The annualized mitigation quantity using the formula referenced above is 667 Tg CO_2 Eq. per year (the flat horizontal line in Figure 4-7). The annualized line can be compared to the third line in Figure 4-7, which is the cumulative annual average over the entire projection period from 2010 to the point in time referenced in the figure. Note that the three annual values (actual, cumulative average, and annualized) are fairly close in value for the first several decades of the projection. Then, as carbon reversal occurs, the actual annual values drop sharply and the cumulative annual estimate drops gradually, while the annualized value, by definition, stays fixed.

Box 4-5: (continued)

Figure 4 7: Comparison of Actual, Cumulative Average, and Annualized GHG Mitigation Value Calculations at $15/t CO_2 Eq.: 2010 2110



The FASOMGHG model allows projection of scenarios out for 100 years; however, policy time frames are likely to be shorter than that. Indeed the results discussions above have tended to focus on results for the first 40 to 50 years after the mitigation scenario is initiated. This raises the question of whether results should be annualized over time frames shorter than 100 years. The results in Figure 4-7 suggest this could make a difference in quantifying a scenario's GHG benefits. To demonstrate this point, Table 4-4 shows how shortening the time horizon for quantifying GHG effects from 100 years to 50 years and 20 years, respectively, changes the annualized mitigation quantity estimate.

The first column in the table presents annualized quantity estimates for each activity and all activities combined when all projected values over the 100-year projection period (positive and negative) are applied to the annualization formula above. As shown in Figure 4-7, the total quantity is about 667 Tg CO_2 Eq. per year. When the annualization is performed over a 50-year period, all effects after 2060 are ignored. This produces a larger annualized estimate (about 760 Tg) because the future reversal of forest and soil carbon in the latter half of the century is not deducted. Shortening the time horizon to 20 years increases the annualized estimate even further (about 790 Tg), because none of the carbon reversal from afforestation and soil carbon management is included (some was included in the 50-year estimate) and thus only the positive accumulations are taken into account. One factor, though, that diminishes the 20-year estimate relative to the 50-year and 100-year estimates is that the latter two include biofuels, and the first estimate does not. The reason that the 20-year estimate does not include biofuels is that biofuel demand will not be sufficient to induce production for several decades at this price ($15/tonne) under assumptions maintained in this analysis. The sensitivity of the model results to the biofuel demand assumptions is explored later in this chapter.

In summary, time dynamics are an important part of the GHG mitigation story in forestry and agriculture, and these effects are emphasized in a number of places throughout this report. However, an annualized estimate provides a theoretically consistent approach to capture these dynamic GHG effects in a single measure, thereby allowing for broad comparisons of mitigation quantities across activities, regions, and price scenarios. The annualized estimate depends on the length of time over which the GHG effects are considered (e.g., 20, 50, ... 100 years). For the purposes of this report, the annualized estimates will typically be presented for the 100-year time horizon, because this is the most complete estimate available and does not ignore potentially important reversal effects in the distant future.

Table 4-4: Comparison of Annualized GHG Mitigation Estimates (Tg CO_2 Eq. per year) across Alternative Time Horizons at a GHG Price of $15/t CO_2 Eq.

	Annualized over ...		
Activity	**100 Years**	**50 Years**	**20 Years**
Afforestation	137.3	164.5	220.0
Forest management	219.1	258.7	244.7
Agricultural soil carbon sequestration	168.0	190.0	243.9
Fossil fuel mitigation from crop production	53.0	46.3	41.6
Agricultural CH_4 and N_2O mitigation	32.0	34.5	38.2
Biofuel offsets	57.2	65.1	0.0
All Strategies	666.7	759.1	788.4

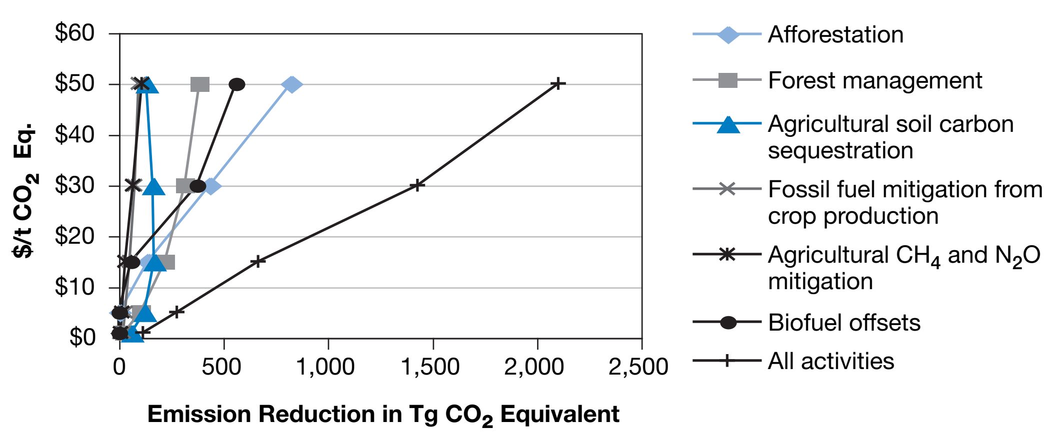
Table 4-5 presents the annualized GHG quantity effects for each major mitigation option by each constant-price scenario. These data constitute a GHG mitigation supply function for U.S. forestry and agriculture, as illustrated in Figure 4-8. The table and figure show that agricultural soil carbon sequestration and forest management are the dominant strategies at low prices, afforestation and biofuels dominate at higher prices, and non-CO_2 gas mitigation in agriculture plays a relatively small role in sector strategies.

Annualized GHG Mitigation by Option. *Afforestation* starts to take hold at the middle price ($15) and becomes the dominant mitigation strategy at the highest prices considered ($30 and $50).[3] This reflects higher opportunity costs of converting agricultural land to forestland than for changes in carbon management practices on forestland and agriculture. It also demonstrates that, once adopted, afforestation can have a larger GHG impact than changes in management within existing uses. Though, as shown above, these effects are quite uneven over time.

Table 4-5: National GHG Mitigation Totals by Activity: Annualized Averages, 2010–2110
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010–2110.

	Constant Prices Over Time				
Activity	**$1**	**$5**	**$15**	**$30**	**$50**
Afforestation	0.0	2.3	137.3	434.8	823.2
Forest management	24.8	105.1	219.1	314.2	384.8
Agricultural soil carbon sequestration	62.0	122.7	168.0	162.4	130.6
Fossil fuel mitigation from crop production	20.5	31.9	53.1	77.6	95.7
Agricultural CH_4 and N_2O mitigation	9.4	15.2	32.0	66.8	110.2
Biofuel offsets	0.0	0.1	57.2	374.6	560.9
All Activities	116.8	277.3	666.7	1,430.4	2,105.4

Figure 4 8: GHG Mitigation Supply Function from National GHG Mitigation Totals by Activity
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



[3] The dominance of afforestation as a strategy is tempered somewhat by exogenous restrictions put on the aggregate contribution of biofuel offsets from the forest and agriculture sectors to reflect current projections of potential biofuel demand by the United States (Haq 2002). The effects of relaxing these biofuel demand restrictions are considered below.

Forest management produces results much like afforestation: fairly small amounts of GHG are sequestered at the lower prices, and larger amounts are only realized at the higher prices. Although the amount of GHG mitigation at the lower prices is small, forest management is second only to agricultural soil carbon in terms of mitigation potential at the two lowest prices.

Agricultural soil carbon sequestration and forest management are the dominant strategies at the lower end of the GHG price range ($1 and $5 per t CO_2). This reflects the relatively low opportunity cost associated with adopting reduced tillage or altering forest management practices to sequester more carbon in some places within the country. These actions can produce results fairly early on.

The increase in other mitigation opportunities actually leads to a slight decline in mitigation through agricultural soil carbon sequestration when moving from the $30 to $50 GHG price. This is because land is being bid away from cropland at these higher GHG prices; therefore, the land base on which to modify tillage practice declines.

Fossil fuel mitigation in crop production plays a very small role in total GHG mitigation at the lower prices, increasing contributions at the higher prices. However, even at the highest price scenario, this activity accounts for less than 3 percent of total mitigation in the first 2 decades.

Agricultural CH_4 and N_2O mitigation. Agricultural non-CO_2 gases are a substantial contributor to the agricultural-sector baseline GHG emissions, as shown in Chapters 2 and 3. However, the non-CO_2 mitigation options provide somewhat limited mitigation potential relative to the CO_2 mitigation and sequestration options.

The activities associated with non-CO_2 gas reductions, such as enteric fermentation, manure management, and soil management, make their largest relative contribution to aggregate mitigation at the lowest price evaluated ($1), where they account for 8 percent of the mitigation portfolio. The share drops to about 5 percent of the portfolio at the $5 price and remains at about 5 percent of total mitigation for all prices above that.

One reason that mitigation potential for the non-CO_2 options is so limited in aggregate terms may be the limited amount of data and other information known about the biophysical and economic consequences of these mitigation options (DeAngelo et al. in press). Another factor may be that what is known about some of the non-CO_2 mitigation options shows that they are profitable under BAU conditions and are thereby incorporated into baseline practices, leaving fewer options available for mitigation beyond the baseline. In either case, more data and research may be needed to better gauge the opportunities for non-CO_2 mitigation options in agriculture.

Biofuels are projected to play a substantially larger role in the mitigation portfolio at higher GHG prices and in later decades. Biofuel results are predicted to increase more than tenfold from 2025 to 2055 (see Table 4.A.1 in the appendix).

Several factors contribute to the incidence and timing of biofuel's role in the mitigation portfolio. First, biofuels are largely uneconomic in the baseline and would take a subsidy to become economically competitive with other fuel sources. A GHG price can serve, essentially, as such a subsidy. As the incentive grows, so does biofuel production. But as explained in Chapter 3, the FASOMGHG model imposes exogenous limits on biofuel demand capacity for several decades. As these limits become less binding over time, adoption increases significantly as well.

Biofuels also do not possess the same reversibility effects as its main competing activities at the high GHG prices. Whereas afforested lands are shown to revert back to agriculture after several decades, biofuel effects are more permanent, both in terms of their ability to offset fossil fuel emissions in the first place and their avoidance of future releases of stored carbon through land-use change or practice reversion.

Sensitivity of National-Level Results to Two Key Assumptions. As discussed in Chapter 3, the FASOMGHG model depends on a wide range of data, parameters, and other assumptions that determine the validity of the model simulations. Of these factors, two stand out as particularly worthy of further scrutiny: (1) the assumed time it takes for a change in agricultural soil tillage practices to achieve a new soil carbon equilibrium (i.e., achieve its "saturation" point) and (2) the assumed rate of market penetration for biofuel demand. Boxes 4-6 and 4-7 present a sensitivity analysis of FASOMGHG model results to changes in these assumptions and finds that the national-level results by activity are moderately affected by changes in the assumed time to achieve the new agricultural soil carbon equilibrium point and the time profile of biofuel demand.

Box 4-6: Sensitivity Analysis of Key Assumption: Time to Reach Soil Carbon Equilibrium ("Saturation")

The FASOMGHG model results for agricultural soil carbon sequestration could depend critically on the assumed time period for soil carbon to reequilibrate to a steady state (or "saturate" as described above) following a change in tillage practice. In FASOMGHG, the annual soil increment following a change in tillage practices is calculated as follows:

$$\Delta Ct = (C_{SSR} - C_{SSC})/T_S \qquad [4.1]$$

where ΔC_t is the estimated annual change in year t; C_{SSR} and C_{SSC} are the soil carbon steady-state values under reduced tillage and conventional tillage, respectively; and T_S is the time to steady state (equilibrium). The carbon steady-state values are given by simulations of the CENTURY model (Parton 1996), but CENTURY does not simulate the T_S variable. Therefore, an assumed value for T_S is needed. Note that ΔCt goes to zero once the new steady state is reached. Therefore, both the size and timing of the annual carbon increment are affected by the assumed length of time to reach the new equilibrium.

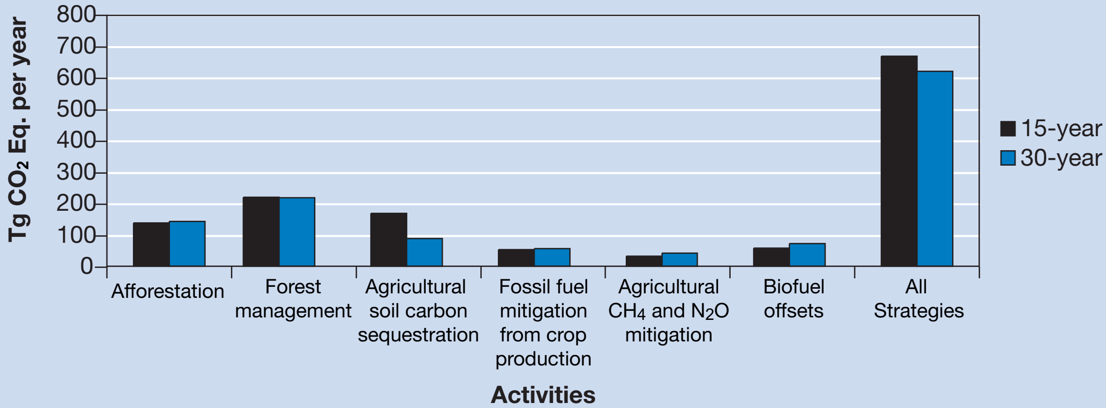
The maintained assumption for the model simulations thus far is that the soil carbon saturation period is 15 years, based on work by West and Post (2002). They quantitatively synthesized the published results of 276 paired treatments of changes in tillage practices from 67 study sites and estimated that the new soil carbon steady state was reached in 10 to 15 years. However, other research has suggested possibly longer saturation periods for tillage change (Lal et al. 1998). To evaluate the sensitivity of the foregoing results to this assumption, the FASOMGHG model was run with an assumed time to equilibrium of 30 years and compared to the results with the 15-year saturation period.

The simulation was run for a constant GHG price of $15, which was selected because all of the mitigation activities come into play at that price. The results in Figure 4-9 are annualized national mitigation estimates for the projection period 2010 to 2110. The annualized contribution of the agricultural soil carbon mitigation declines by almost half, from about 170 Tg CO_2 per year to 90 Tg per year, which is about what one might expect when the time to equilibrium is doubled, and therefore the annual increment calculation in equation [4.1] is halved (assuming the same quantity of mitigation). However, that is not the end of the story. The figure illustrates that not only is there the expected reduction in annual mitigation from agricultural soil carbon sequestration when the saturation period is elongated, but also the contribution of other activities is affected as well. In particular, the reduction in agricultural soil carbon mitigation is partly offset by increased mitigation from biofuel offsets and agricultural CH_4 and N_2O mitigation and to a lesser extent forest carbon and fossil fuel mitigation. The net reduction in mitigation across all activities is under 50 Tg CO_2 per year, so the initial 80 Tg reduction from soil carbon is offset by about a 30 Tg net increase in the other activities. In essence, this shows that GHG mitigation options compete with each other on a fixed land base. When one option becomes less advantageous, the competing options can take up some of the slack.

Box 4-6: (continued)

Figure 4 9: Model Sensitivity to Saturation Period toward a New Soil Carbon Equilibrium from Tillage Change: GHG Price = $15/t CO_2 Eq.

Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



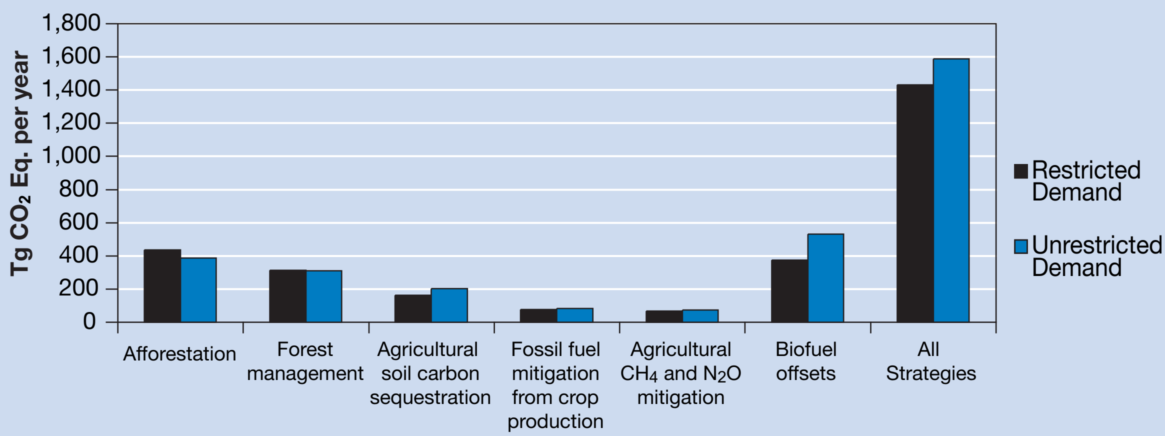
Box 4-7: Sensitivity Analysis of Key Assumption: Biofuel Demand

The FASOMGHG model was modified in this report to confine biofuel production to fall within the capacity limits projected by the EIA's energy forecasts (Haq 2002). As such, some biofuel mitigation that may initially seem profitable within FASOMGHG is excluded for consistency with the EIA estimates. To test for the sensitivity of this assumption, the model was re-run to relax the EIA demand assumption and rely purely on the profitability of biofuel production as a determinant of total biofuels supplied to the market.

The results of this simulation are illustrated in Figure 4-10. The simulation was run at a GHG price of $30/t CO_2 Eq. (constant), which is the price at which biofuels become a substantial contributor to national mitigation totals. Relaxing the biofuel demand restriction raises the contribution of that activity for sensitivity analysis from 375 to 530 Tg CO_2 Eq. per year, more than a 40 percent increase. As with the agricultural soil carbon example, we must consider offsetting effects from the other activities, but they are not all negative. The contribution of afforestation declines as part of the mitigation portfolio, but the contribution of agricultural soil carbon and non-CO_2 mitigation rises, indicating there are complementarities between biofuel production and mitigation from these activities. Notably, land that is diverted from traditional crops to biofuel production tends to sequester more carbon and release less N_2O and CH_4.

Figure 4 10: Sensitivity of Model Results to Assumed Biofuel Demand Restrictions: GHG Price = $30/t CO_2 Eq.

Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



GHG Mitigation by Region

Because the U.S. landscape is quite heterogeneous, the adoption and effectiveness of GHG-mitigating activities will not be uniform across regions within the country. The regional definitions used in this section can be found in Table 3-2 in Chapter 3.

The regional totals distribution at the middle three constant-price scenarios ($5, $15, and $30/t CO_2 Eq.) are illustrated in Figure 4-11. This figure and the corresponding table (Table 4.A.2 in the appendix) with activity detail provide a summary of annualized GHG mitigation quantities by major region, activity, and price scenario. Table 4.A.3 in the appendix reports the regional breakdown of annualized mitigation totals by all key activities modeled.

By and large, the regions with the highest GHG mitigation are the South-Central, Corn Belt, and Southeast regions. At the lower GHG prices, the Lake States and Great Plains are key contributors as well. The contributions of the Corn Belt, Lake States, and Great Plains are primarily in the form of agricultural soil carbon sequestration, whereas the South-Central and Southeast regions are primarily suppliers of carbon sequestration from afforestation and forest management.

The Rockies, Southwest, and Pacific coast states generate relatively small shares of the national mitigation total under all of the price scenarios. From those regions, only forest management from the PNWW produces appreciable mitigation. This is because climate and topography significantly limit the movement of land between major uses such as forestry and agriculture in the western regions.

When biofuel production is selected at the higher GHG prices, this occurs primarily in the Northeast, South, Corn Belt, and Lake States.

Figure 4 11: Total Forest and Agriculture GHG Mitigation by Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.

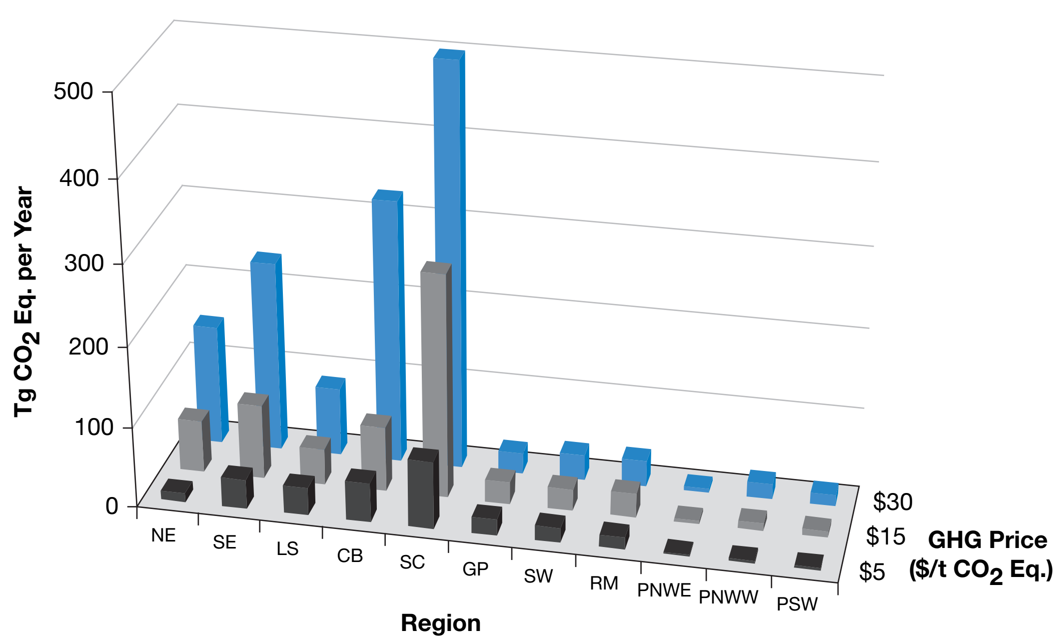


Table 4-6 presents a top 10 ranking of region–activity combinations producing the most GHG mitigation by price scenario. This table illustrates how the distribution of GHG mitigation opportunities varies across regions and activities as the GHG price changes. At the lowest two prices, the top-ranked combination is forest management in the South-Central region, followed by agricultural soil carbon sequestration in the Corn Belt and Lake States. As prices rise, so do the opportunities for afforestation in the South-Central and Corn Belt regions and biofuel production in the Corn Belt, South, and Northeast.

Non-GHG Environmental Co-effects

The undertaking of GHG mitigation activities and the resultant shift of land uses and management practices have the potential to produce environmental co-effects other than climate change mitigation. For instance, the changes in agricultural practices can have an effect on the farm inputs applied, which in turn can affect the loadings of nutrients, erosion, and other residuals into waterbodies.

Table 4-6: Top 10 Region-Activity Mitigation Combinations
Ranks are based on mitigation quantities annualized over the period 2010–2110.

		GHG Constant Price Scenario (\$/t CO_2 Eq.)				
Region	**Activities**	**\$1**	**\$5**	**\$15**	**\$30**	**\$50**
SC	Forest management	1	1	1	3	3
CB	Agricultural soil carbon sequestration	2	2	4	7	10
LS	Agricultural soil carbon sequestration	3	3	6		
GP	Agricultural soil carbon sequestration	4	5	7		
SW	Fossil fuel mitigation from crop production	5	7			
RM	Agricultural soil carbon sequestration	6	8			
SC	Fossil fuel mitigation from crop production	7	6	8	10	
NE	Agricultural soil carbon sequestration	8	9			
CB	Fossil fuel mitigation from crop production	9	10			
CB	Agricultural CH_4 and N_2O mitigation	10				
SE	Forest management		4	3	6	8
SC	Afforestation			2	1	2
NE	Biofuel offsets			5	4	5
RM	Afforestation			9		
SW	Agricultural soil carbon sequestration			10		
CB	Afforestation				2	1
SE	Biofuel offsets				5	4
SC	Biofuel offsets				8	6
CB	Biofuel offsets				9	7
LS	Afforestation					9

To briefly assess these effects, the analysis focuses on a single GHG price ($15/t CO_2 Eq.), as shown in Figure 4-12. Three of the four pollutants reveal a reduction in overall loadings relative to baseline amounts. Phosphorous and erosion loadings reveal the largest reduction of approximately 40 percent each. This reduction in pollutant loadings is tied to the widespread adoption of conservation or zero tillage practices, which reduces erosion and phosphorous runoff that often adheres to soil particles.[4] Over time, however, these loadings return closer to baseline levels. Pesticides are the only loadings that exceed baseline loadings in some cases. This finding reflects the fact that adopting no-till farming practices often requires increased pesticide applications, as chemical means of weed control replace mechanical means.

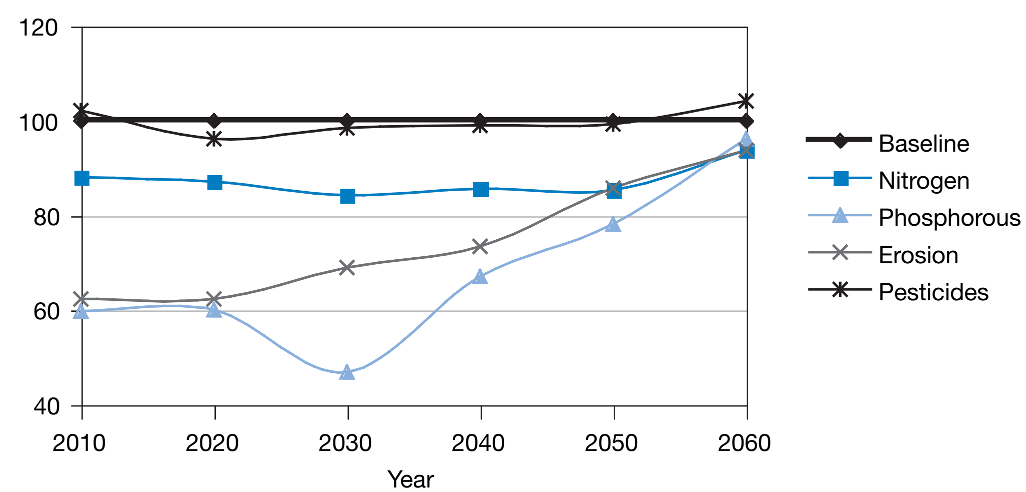
Chapter 7 expands the discussion of environmental co-benefits by evaluating the full range of constant GHG prices, evaluating the net likely impact of these loadings patterns on water quality and considering other environmental co-effects such as biodiversity.

Mitigation Response to Rising GHG Price Scenarios

Up to this point, the chapter has focused on results for the constant GHG price scenarios. Now results from the rising-price scenarios are discussed. The focus of the discussion is primarily on the differences from the constant-price results. A detailed table of mitigation results by activity in key years for the rising-price scenarios is presented in the appendix to this chapter (Table 4.A.4).

As with the constant-price scenarios, there is a larger amount of GHG mitigation with the higher rising-price scenarios; however, the major difference between the constant- and rising-price scenarios is the timing of the mitigation. These timing effects are illustrated in Figure 4-13. As shown earlier, the GHG mitigation totals start high in 2015 and then decline by 2055 under the constant-price scenarios. The rising-price scenarios, however, tend to show the opposite effect. Mitigation is minimal in the early years when prices are low but rises substantially in the later years as the prices escalate for two of the

Figure 4 12: Pollutant Loading Effects Over Time of a $15/t CO_2 Eq. GHG Price



Note: All values indexed to a baseline value of 100.

[4] Recall from Table 4-3 that the $15 carbon price in the year 2015 resulted in the largest conversion of conventional till to either conservation or zero tillage practices.

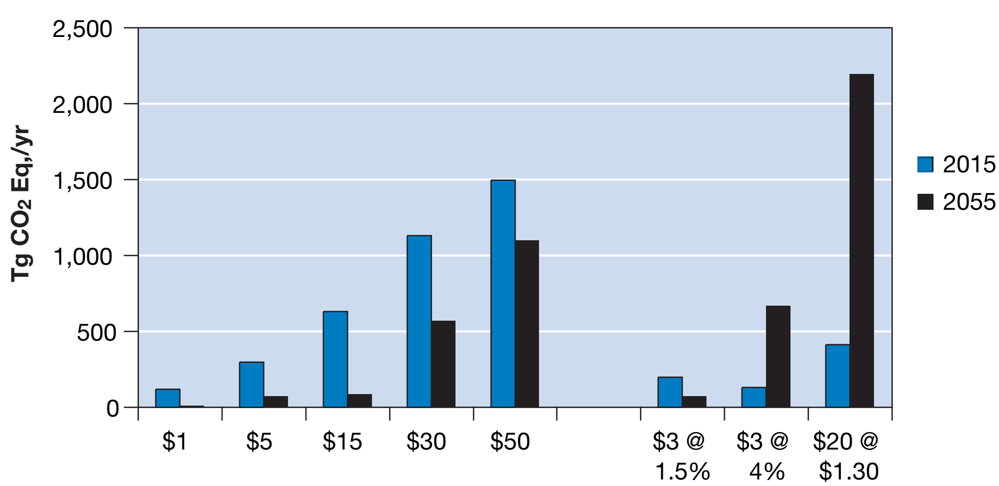
three scenarios. To a large extent, this time pattern of mitigation is the result of the producers of GHG mitigation holding out for the higher prices that occur in the later years of the projection. This is particularly crucial with mitigation options because carbon sequestered early on cannot be re-sequestered in the future. When prices are expected to rise, this provides an incentive to wait on enacting sequestration activity.

Figure 4-14 illustrates cumulative GHG effects over time for the two scenarios that have an initial price of $3 and rise at 1.5 percent and 4 percent, respectively. The main differences between the two scenarios are as follows:

- The scenario with the 4 percent rate of increase demonstrates a substantial delay in mitigation activity, as suppliers wait for the much higher prices to come in the future. Once prices near their $30 cap at mid-century, significant action takes hold.
- The level of mitigation ultimately obtained is substantially larger in the 4 percent scenario, primarily because the price gets much higher in the out years. As such, the biofuel option becomes more attractive. The biofuel option also favors later adoption because the demand for biofuels over time reflects the assumption that the capacity for biofuel use in electricity generation is heavily constrained in the short run but could expand substantially in the long run.

Figure 4-15 shows cumulative GHG mitigation for the more aggressive rising-price scenario, starting at $20/t CO_2 Eq. and rising to $75. This case also produces delay in mitigation but includes a much larger quantity of mitigation than the other two scenarios and has a larger role for afforestation because of the higher starting and ending prices. These figures reveal the expected differences resulting from the higher prices, while highlighting the timing effects that are not seen in the constant-price scenarios.

Figure 4 13: Constant Price Scenarios vs. Rising Price Scenarios and GHG Mitigation
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for 2015 and 2055.



Note: All values indexed to a baseline value of 100.

Figure 4 14: Cumulative GHG Mitigation over Time: $3/t CO_2 Price Rising at Two Rates
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.

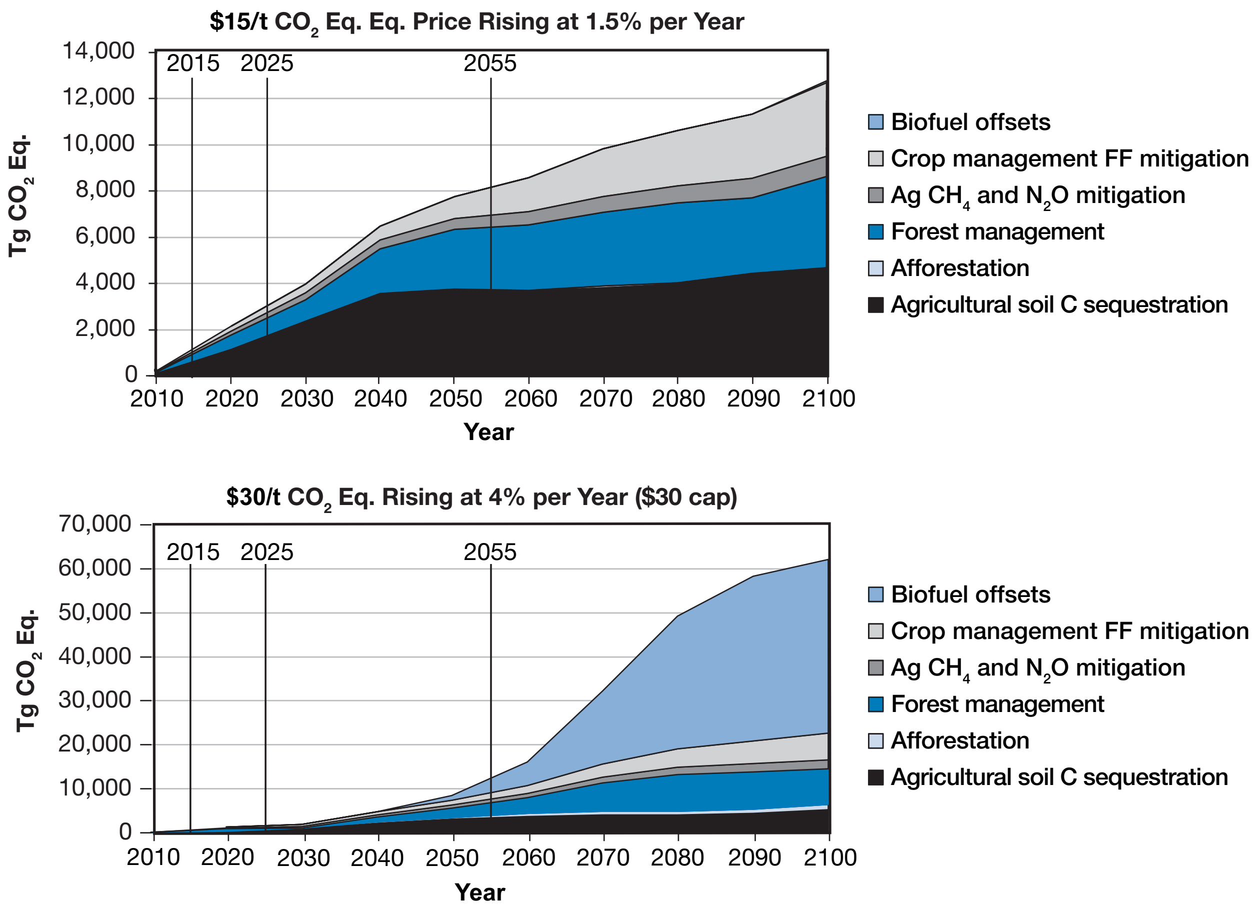
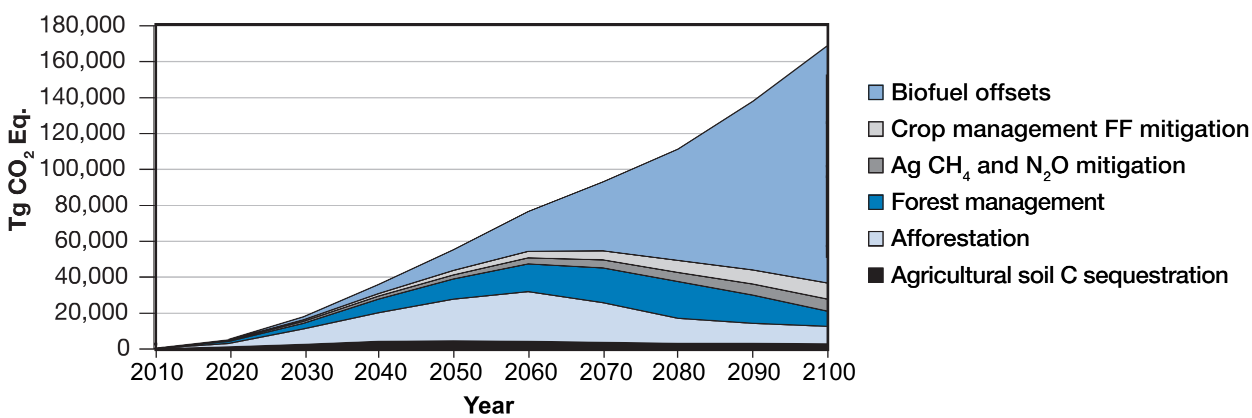


Figure 4 15: Cumulative GHG Mitigation over Time: $20/t CO_2 Price Rising by $1.30 per Year ($75 cap)
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.



Comparison of FASOMGHG Results with Other Analyses

It is useful to compare the results of the analysis presented in this chapter to similar economic studies of GHG mitigation in the U.S. forest and agriculture sectors. It is important to note, however, that this study is rather unique in terms of its depth and breadth of mitigation options covered across the two sectors. In essence, this is a somewhat more comprehensive and integrated assessment of economic potential of the U.S. forest and agriculture sectors together than other studies to date. So a direct and consistent comparison with other studies is not quite possible. However, several studies have looked separately at the national mitigation potential from afforestation, forest management, and agriculture and can thereby provide context for the core results presented above.

Richards and Stokes (2004): Forest Carbon

Richards and Stokes (2004) conducted a thorough review of 36 forest carbon sequestration economic studies throughout the world. Among this group, eight studies estimated marginal cost functions for forest carbon sequestration at the national level for the United States, reportable on an annual basis. Consequently, these eight studies are directly comparable to the results presented in this chapter, once the appropriate adjustments are made to tonnes of CO_2 Eq. per year.[5] Table 4-7 summarizes the range of carbon sequestration quantity and cost results for the eight comparable U.S. studies reviewed by Richards and Stokes and compares them to the results from the constant-price FASOMGHG simulations in this study. The aggregate national forest carbon sequestration estimates in the Richards and Stokes studies ranged from 147 to 2,349 Tg CO_2 Eq./yr at a cost (price) ranging from \$1.36 to \$40.87 per t CO_2 Eq. Most of these studies examine afforestation only or do not break out afforestation from forest management. Only one of the studies presents results for forest management activities, and that study produced an estimate of roughly 400 Tg CO_2 Eq./yr of sequestration at a cost ranging from \$1.63 to 12.81/t CO_2 Eq.

Many compounding factors cause the results to vary widely in the studies reviewed by Richards and Stokes, including but not limited to the extent of ecosystem components included in the carbon calculations, the biophysical foundation for the

Table 4-7: Comparison of FASOMGHG Results in this Chapter to Range of Estimates from Richards and Stokes' (2004) Review Study

	Carbon Sequestration (Tg CO_2 Eq. per Year)				
	This Study: Comprehensive Activities, Annualized Over 2010–2110				Richard and Stokes: U.S.-Based Studies
	GHG Price Scenario (\$/t CO_2 Eq.)				GHG Price Range (\$/t CO_2 Eq.)
Activity	**\$5**	**\$15**	**\$30**	**\$50**	**\$1.36 – \$40.87**
Afforestation	2.3	137	435	823	147 – 2,349
Forest management	105	219	314	385	404[a]
Total forest carbon	107	356	749	1,208	551 – 2,753

[a] Only one study covering the United States included estimates for forest management.

[5] The eight comparable studies are Moulton and Richards (1990), Adams et al. (1993), Parks and Hardie (1995), Callaway and McCarl (1996), Alig et al. (1997), Richards (1997), Adams et al. (1999), and Stavins (1999). Unfortunately, Richards and Stokes did not adjust the studies' results to put them in a common year for dollar comparisons.

carbon sequestration rates used, and the land costs included in cost calculations. However, comparing the U.S. forest carbon sequestration estimates generated by the FASOMGHG results earlier in the chapter suggests they fall well within the range of estimates found in the Richards and Stokes review. FASOMGHG mitigation estimates will generally not reach the high end of the estimates found in the Richards and Stokes study, because FASOMGHG employs economic feedback effects (e.g., timber and agricultural price effects) that will temper sequestration responses, in contrast to studies that estimate mitigation cost functions without market feedback effects.

Stavins (1999): Afforestation

For a further comparison of this chapter's results to other studies, we look at research conducted by Stavins (1999) that synthesized the results from several past studies that were directly comparable to the results presented in his work in that they were national (United States) in scale and focused specifically on afforestation. Stavins computes a 95 percent confidence interval on his national marginal cost function for afforestation and shows that other previously published studies (Richards et al. 1993, Adams et al. 1993, and Callaway and McCarl 1996) fall within that interval.

To compare the results from this study to Stavins', several adjustments needed to be made. First, Stavins' results are presented graphically via a marginal cost function. This enabled one to trace the amount of carbon sequestered nationally to a given level of marginal cost per tonne sequestered. Conceptually, this is similar to evaluating the total amount of carbon that can be sequestered at a given GHG price. This enables direct comparison with the FASOMGHG results presented above. However, further adjustment is necessary to compare Stavins' results, which are expressed in short tons of carbon and 1990 dollars, with the results here, which are in tonnes of CO_2 equivalent and 2000 dollars.[6] These adjustments are made and results are compared in Table 4-8 for the \$30 and \$50 constant-price scenarios, which are the two scenarios in which forest carbon plays the largest role.

The main implication from the comparative results presented in Table 4-8 is that the core scenario analysis in this report suggests a smaller aggregate potential for forest carbon sequestration than that found in the Stavins study. When this study's afforestation carbon potential is compared to Stavins, which is the most relevant comparison, the mitigation quantities are about one-third to one-half of Stavins' estimates. When forest management is added to the totals from this study, the relative quantities are one-half to three-quarters of the Stavins' estimates.

Table 4-8: Comparison of FASOMGHG Results in this Chapter to Stavins' (1999) Study

	Carbon Sequestration (Tg CO_2 Eq. per Year, above baseline, annualized over 100-year time period)	
	GHG Price (\$/t CO_2 Eq.)	
	\$30	\$50
This Study		
Afforestation	435	823
Forest management	314	385
Total forest carbon	749	1,208
Stavins' Central Estimate[a]	1,330	1,660
This Study as % of Stavins'		
Afforestation	33%	49%
Total forest carbon	56%	73%

[a] Adjustments made to convert Stavins' estimates from 1990 dollars per short ton to 2000 dollars per t CO_2 Eq.

[6] Short tons of carbon are converted to tonnes by dividing by 1.102. Tonnes of carbon are converted to tonnes CO_2 by multiplying by 3.667. 1990 dollars are converted to 2000 dollars using the consumer price index (urban consumers) <www.bls.gov/cpi/home.htm>.

Stavins' paper asserts that one might typically expect econometric estimates, like those in his study, to yield smaller mitigation quantities than estimates using optimization methods like the FASOMGHG model, because of the econometric reliance on "revealed preferences" of landowners.

However, while FASOMGHG does not incorporate the revealed behavior of an econometric model, it does capture (unlike the Stavins study) feedbacks from the commodity and land markets that need to be considered when estimating the net effects of large-scale programs. Large-scale movement of land from agriculture to forests will tend to raise agricultural prices and lower timber prices. This provides an incentive for countervailing movements of land from forest to agricultural use. The multimarket equilibrium nature of FASOMGHG captures these feedbacks and slows the afforestation (and sequestration) process accordingly. Ignoring this feedback tends to overstate sequestration potential all else equal, as Stavins acknowledges in his paper.

Sedjo, Sohngen, and Mendelsohn (2001): Forest Carbon

Since the Stavins (1999) study, other forest carbon sequestration studies have been published that are in some ways comparable to those synthesized by Stavins (see, for instance, Adams et al. [1999], Plantinga et al. [1999], Stavins and Newell [2000], Sedjo, Sohngen, and Mendelsohn [SSM] [2001], and Sohngen and Mendelsohn [2003]). Perhaps the most directly comparable of those studies is the SSM 2001 study, which looks at a wide range of price scenarios similar to the constant-price scenarios in this chapter. The one important difference, though, is the SSM results are for all of North America, while these results are for the United States. Nevertheless, U.S. results are by far the dominant component of the North America results in SSM. Table 4-9 compares SSM results at $50 and $100 per tonne of carbon ($13.62 and $27.25 per t CO_2 Eq.) with the closest points of comparison in this study ($15 and $30 per t CO_2 Eq.).[7]

The SSM mitigation estimates are about one-quarter less than the FASOMGHG results under both price levels. While this is somewhat surprising given the larger continental coverage of the SSM study, many modelers would consider a 25 percent variation in such macro-scale results using two different models a reasonably good correspondence. Further examination of the two models' results suggests that the differences are primarily due to the more detailed modeling of land opportunity costs in U.S. agriculture in FASOMGHG. This produces a more elastic afforestation response than the SSM study, which relies on a single inelastic land-use supply function from agriculture.

Table 4-9: Comparison of FASOMGHG Forest Carbon Sequestration Results in this Chapter with Sedjo, Sohngen, and Mendelsohn (2001)

Quantities for both studies are Tg CO_2 Eq. per year, sequestration above baseline, annualized over 100-year time period.

Sedjo, Sohngen, and Mendelsohn (2001) Scenario	Total Forest Carbon Sequestration (Tg CO_2 Eq. per Year)	This Study Scenario	Total Forest Carbon Sequestration (Tg CO_2 Eq. per Year)
$13.62/t CO_2 Eq. ($50.00/t C Eq.)	265	$15/t CO_2 Eq.	356
$27.25/t CO_2 Eq. ($100/tC Eq.)	563	$30/t CO_2 Eq.	749

[7] The direct comparison between this study's results and those of SSM was enabled with data provided by Dr. Sohngen that is not directly presented in one of the paper's tables.

USDA, Economic Research Service (2004): Agricultural Carbon Sequestration

Most recently a report by the USDA ERS was published that examined the economics of sequestering carbon in the agriculture sector (Lewandrowski et al. 2004). That report examines mitigation options in the agriculture sector, including afforestation but excluding forest management and biofuels. The ERS study produced estimates for the amount of carbon that could be sequestered over a 15-year time period given various carbon prices expressed in \$/t C. After converting these to \$/t CO_2 Eq. the prices range from \$2.72 to \$34.05 per tonne (see Table 4-10).

These prices are introduced in a model of the U.S. agriculture sector (USMP), which is a spatial market equilibrium model. All mitigation estimated by this model is relative to a baseline generated by the model. The USMP model results are also separated by forest and soil sequestration, allowing for a comparison to the FASOMGHG soil results. At the lowest GHG price, the amount of overall carbon sequestered ranged from 0.4 to 35 Tg CO_2 Eq. per year. The highest price investigated resulted in total sequestration ranging from 237 to 587 Tg CO_2 Eq. per year.

The range of estimates presented in the USDA ERS report is generally lower than the range of estimates generated by FASOMGHG in this study, for a comparable set of activities and time horizon (15 years). These differences can be expected based on the differences in the models and assumptions embedded in the estimates. Note that the FASOMGHG estimates for these price scenarios are lower when we look over time periods longer than 15 years. However, we cannot compare longer time horizon estimates to the ERS study, which takes a static snapshot of a 15-year program.

Recap of Study Comparisons

Although not a comprehensive comparison of the results of this study to the entire spectrum of results in the literature, the comparisons above provide some validation that the results of various components analyzed here are within the (fairly wide) range of mitigation estimates found in similar economic studies. Differences across the studies can be explained in large part by differences in methodology and geographic coverage. Taken together, these comparisons suggest that the FASOMGHG model produces results that, while more comprehensive in its coverage of both forestry and agriculture than most other studies, are consistent with findings on different component parts (afforestation, forest management, and agricultural soil carbon sequestration).

Table 4-10: Comparison of this Study with Lewandrowski et al. (2004) (USDA ERS)

	This Study (Tg CO_2 Eq./yr net emissions reduction below baseline) After 15 years (Yr. 2025)				USDA ERS (Tg CO_2 Eq./yr) Average annual mitigation for 15-year program					
GHG Price (\$/t CO_2 Eq.)	\$5	\$15	\$30	\$50	\$2.72	\$6.80	\$13.60	\$20.40	\$27.50	\$34.05
Afforestation	12	228	806	1,296	0–31	20–140	105–264	145–378	174–460	224–489
Agricultural soil carbon sequestration	149	204	187	153	0.4–4	3–10	3–30	5–48	11–70	13–95
Total	161	432	994	1,449	0.4–35	25–151	108–295	151–426	185–529	237–587

Appendix 4.A

This appendix provides detailed tabular results that are referenced in the main text of this chapter.

Table 4.A.1: Key Results at the National Level by Activity, Time Period, and Constant-Price Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for representative years 2015, 2025, and 2055.

		GHG Price (\$/t CO_2 Eq.)				
Year[a]	**Activity**	**\$1**	**\$5**	**\$15**	**\$30**	**\$50**
2015	Afforestation	0	0	145	557	877
	Forest management	27	121	227	271	301
	Agricultural soil carbon sequestration	66	139	194	191	177
	Fossil fuel mitigation from crop production	17	23	35	46	55
	Agricultural CH_4 and N_2O mitigation	11	15	28	48	69
	Biofuel offsets	0	0	0	16	17
	All activities	121	298	629	1,129	1,496
2025	Afforestation	0	12	228	806	1,296
	Forest management	22	89	156	250	309
	Agricultural soil carbon sequestration	67	149	204	187	153
	Fossil fuel mitigation from crop production	14	18	32	49	62
	Agricultural CH_4 and N_2O mitigation	7	17	36	76	119
	Biofuel offsets	0	0	0	21	83
	All activities	110	285	655	1,390	2,021
2055	Afforestation	1	–7	–270	–873	–426
	Forest management	–10	48	171	322	325
	Agricultural soil carbon sequestration	1	–26	–22	–10	–30
	Fossil fuel mitigation from crop production	14	49	62	92	111
	Agricultural CH_4 and N_2O mitigation	7	11	26	52	101
	Biofuel offsets	0	0	121	990	1,021
	All activities	13	74	86	572	1,101

Table 4.A.2: Total Forest and Agricultural GHG Mitigation by Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010-2110.

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
NE	10.9	64.7	148.1
SE	36.4	92.6	236.0
LS	34.6	44.8	84.9
CB	49.0	80.8	326.4
SC	83.9	278.1	507.5
GP	20.5	27.3	25.5
SW	18.1	26.7	31.7
RM	15.3	29.8	32.7
PNWE	2.2	4.3	4.8
PNWW	3.2	9.6	19.1
PSW	3.2	8.0	13.8

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010-2110.

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
Afforestation			
CB	2.0	6.6	162.5
LS	0.0	0.0	14.9
PNWE	0.3	1.6	2.3
PSW	0.0	1.6	2.4
RM	0.0	11.7	11.8
SC	0.0	115.8	228.6
SE	0.0	0.0	12.4
US	2.3	137.3	434.8
Forest Management			
CB	-3.0	-5.6	-5.5
LS	0.8	5.7	14.2
NE	1.9	9.5	23.6
PNWE	0.2	0.2	0.4
PNWW	3.2	9.6	19.1
PSW	0.7	0.8	2.9
RM	1.9	2.0	4.7
SC	70.6	127.7	160.8
SE	28.8	69.2	93.9
US	105.1	219.1	314.2
Agricultural Soil Carbon Sequestration			
CB	39.5	62.2	72.4
GP	20.0	29.3	33.2
LS	33.3	36.9	33.1
NE	6.9	4.7	-3.7
PNWE	1.5	2.4	2.7
PSW	0.3	0.7	0.9
RM	7.5	9.5	9.6
SC	4.5	4.3	-6.0
SE	3.8	7.6	7.0
SW	5.5	10.5	13.2
US	122.7	168.0	162.5

(continued)

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario (continued)

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
Fossil Fuel Mitigation from Crop Production			
CB	6.5	10.5	21.7
GP	1.0	0.8	-0.4
LS	0.4	1.0	1.8
NE	1.1	1.7	1.2
PNWE	0.2	0.2	0.0
PSW	1.3	2.3	3.4
RM	1.2	1.3	1.4
SC	10.2	23.7	33.4
SE	1.3	1.9	5.8
SW	8.7	9.7	9.3
US	31.9	53.1	77.6
Agricultural CH_4 and N_2O Mitigation			
CB	4.1	7.4	24.2
GP	-0.8	-3.3	-8.5
LS	0.1	1.1	1.6
NE	0.9	1.0	1.8
PNWE	0.0	-0.1	-0.6
PSW	0.9	2.7	4.3
RM	4.7	5.2	5.1
SC	-1.1	6.9	21.0
SE	2.5	4.7	9.2
SW	3.9	6.4	8.9
US	15.3	32.0	66.8
Biofuel Offsets			
CB	-0.1	-0.3	51.1
GP	0.3	0.6	1.1
LS	0.1	0.1	19.3
NE	0.0	47.9	125.1
PNWE	0.0	0.0	0.1
PSW	0.0	0.0	0.0
RM	0.0	0.0	0.2
SC	-0.3	-0.4	69.9
SE	0.0	9.2	107.5
SW	0.1	0.1	0.3
US	0.1	57.2	374.6

(continued)

Table 4.A.3: Forest and Agricultural GHG Mitigation by Activity, Region, and Price Scenario (continued)

	GHG Price ($/t CO_2 Eq.)		
Region	**$5**	**$15**	**$30**
All Activities			
CB	49.0	80.8	326.4
GP	20.5	27.3	25.5
LS	34.6	44.8	84.9
NE	10.9	64.7	148.1
PNWE	2.2	4.3	4.8
PNWW	3.2	9.6	19.1
PSW	3.2	8.0	13.8
RM	15.3	29.8	32.7
SC	83.9	278.1	507.5
SE	36.4	92.6	236.0
SW	18.1	26.7	31.7
US	277.3	666.7	1,430.4

Table 4.A.4: Key Results at the National Level by Activity, Time Period, and Rising Price Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for representative years 2015, 2025, and 2055.

Year[a]	Activity	\$20 @ \$1.30/yr	\$3 @ 1.5%/yr	\$3 @ 4%/yr
2015	Afforestation	132	0	7
	Forest management	101	61	62
	Agricultural soil carbon sequestration	105	103	25
	Fossil fuel mitigation from crop production	38	20	21
	Agricultural CH_4 and N_2O mitigation	31	13	14
	Biofuel offsets	4	0	0
	All activities	411	198	129
2025	Afforestation	649	4	11
	Forest management	176	21	–67
	Agricultural soil carbon sequestration	135	116	48
	Fossil fuel mitigation from crop production	47	17	18
	Agricultural CH_4 and N_2O mitigation	59	15	18
	Biofuel offsets	153	0	0
	All activities	1,218	174	28
2055	Afforestation	565	–3	15
	Forest management	423	19	141
	Agricultural soil carbon sequestration	–26	–3	76
	Fossil fuel mitigation from crop production	113	50	62
	Agricultural CH_4 and N_2O mitigation	101	12	25
	Biofuel offsets	1,021	0	352
	All activities	2,196	75	671

[a] Year represents midpoint of decade tracked in FASOMGHG model (e.g., 2015 represents the midpoint of the 2010 to 2019 decade).

CHAPTER 5

Mitigation Potential of Selected Activities

Chapter 5 Summary

GHG mitigation for forestry and agriculture is considered on a more limited scale than the comprehensive coverage assessed in Chapter 4. Scenarios include fixed time-specific (Year 2025 and Year 2055) GHG mitigation quantities from forestry and agriculture, payments for CO_2 only (vs. for all GHGs), and payments for selected mitigation activities.

For fixed time-specific scenarios, the effectiveness of GHG mitigation depends on the size of the fixed mitigation quantity and whether efforts to maintain that level of mitigation remain in place or expire. Aiming for future annual mitigation levels could lead to unintended GHG releases in preceding years. This is particularly relevant for forest carbon. Aiming for cumulative, rather than annual, mitigation could address this problem.

Paying for CO_2 mitigation only does not significantly diminish the net GHG mitigation potential of forestry and agriculture compared to scenarios where payments for all GHGs are made, since most GHG mitigation occurs through sequestration and CO_2 reductions. Non-CO_2 reductions prove to be complementary to—and thus occur with—CO_2 mitigation.

Scenarios in which only agricultural activities are carried out can achieve moderate levels of GHG mitigation, even at fairly low cost. Forest carbon sequestration and biofuels contribute more substantially at somewhat higher price scenarios or when price scenarios rise over time. Agricultural GHG mitigation opportunities are widely distributed across the United States, but most forest GHG mitigation opportunities occur in the South.

The previous chapter evaluated GHG mitigation potential under scenarios for all three critical GHGs (CO_2, CH_4, and N_2O) across all agricultural activities and carbon sequestration options in forestry and agriculture. As the results indicate, a comprehensive payment approach has the potential for large-scale mitigation, potentially generating up to 2,000 Tg CO_2 (2 billion tonnes CO_2 Eq., or about 550 Tg C Eq.) per year of mitigation.

However, for several reasons forestry and agriculture's role in national GHG mitigation might involve less than comprehensive coverage of all activities and GHGs (Sampson 2003; Richards et al. forthcoming):

- Much of the focus to date on GHG mitigation has been on emissions from energy-producing sectors, while the role of forestry and agriculture has been seen more as a cost-effective means to offset emissions from these other sectors.
- Some GHG-emitting (sequestering) activities in forestry and agriculture are difficult to measure, monitor, and verify and could thereby be difficult to include in a comprehensive accounting and incentive approach.
- Individual sources of emissions and sequestration tend to be small and widely dispersed over the landscape, making cost-effective aggregation of mitigation activities potentially difficult.

Because of these issues, it is reasonable to evaluate smaller-scale mitigation than that assessed in Chapter 4. In this case, some activities, GHGs, and locations might be subject to mitigation activities and incentives, while other activities, GHGs, and locations might not be covered. Many potential selected activity combinations or mitigation quantities are feasible. A few are reviewed here to explore the implications of limiting activities or quantities of GHG reductions or sequestration:

- setting a fixed national GHG mitigation quantity for a selected date (e.g., 375 Tg CO_2 Eq. per year in 2025),
- paying for GHG mitigation only for selected gases (e.g., CO_2 only), and
- paying for GHG mitigation only for selected activities (e.g., agricultural soil carbon only).

This chapter continues first with an analysis of several hypothetical aggregate national GHG mitigation levels for the combined forest and agriculture sectors. The fixed quantities assessment is followed by evaluations of GHG payments that are limited either in terms of the GHGs covered, the activities covered, or the prices paid. Such an approach could be similar in many ways to project-based mitigation, in which initiators of a GHG mitigation project take actions to reduce emissions or increase sequestration on site and quantify and report these net reductions.

Fixed Quantities of National GHG Mitigation

The three scenarios evaluated in this section are defined in Table 5-1. Each scenario sets a fixed level of reduced net emissions by 375 Tg CO_2 (just over 100 Tg carbon) per year below the BAU GHG baseline for the two sectors by the year 2025.

The three scenarios explore the effect of maintaining, increasing, or dropping an early, initial mitigation level in the out years. In the first case (T-375-375), the 2025 mitigation level is kept in place thereafter through the end of the projection. In the second scenario (T-375-900), the 2025 quantity is increased from 375 Tg CO_2 to 900 Tg CO_2 (250 Tg C) per year by the year 2055, remaining at that level thereafter. Under the third scenario (T-375-0), once the 2025 mitigation quantity is achieved, no aggregate quantity is specified thereafter. To put this in context, 375 Tg and 900 Tg CO_2 Eq., would respectively offset about 5 and 13 percent of the U.S. GHG emission totals for 2003 (EPA 2005).

Table 5-1: National GHG Mitigation Quantity Scenarios for 2025 and 2055

All quantities are measured in Tg CO_2 Eq. per year net emission reductions below baseline.

Quantities for 2025 and 2055 can be met by achieving average annual reductions for the representative decade (2020–2030, and 2050–2060), respectively.

Scenario	U.S. Quantity, 2025	U.S. Quantity, 2055
T-375-375	375	375
T-375-900	375	900
T-375-0	375	0

The analysis uses FASOMGHG to find the solution to the least-cost combination of activities and locations to achieve given national mitigation levels for the forest and agriculture sectors.

National-Level Results by Activity and Time Period

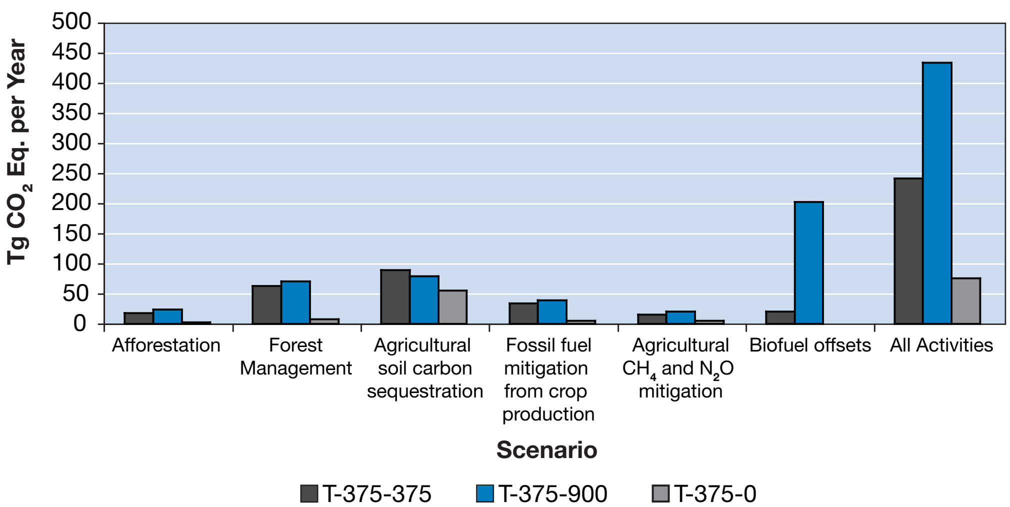
The results of the FASOMGHG simulations for the three national mitigation quantity scenarios are summarized in Table 5-2 and Figure 5-1. They present national mitigation results that are annualized for the entire 100-year projection period by activity. These results report the national-level GHG quantities and marginal cost of the activity mix that the model identifies as likely to be implemented to achieve the given GHG reduction quantity, for the target date, at least cost. Some key results are the following:

- **The scenario that fixes the national mitigation quantity at 375 Tg per year from year 2025 and beyond achieves that quantity with a broad mix of activities.** While agricultural soil carbon sequestration and forest management make the largest contribution, as in the lower-

Table 5-2: National Mitigation, by Scenario and Activity, for Least-Cost Quantity in 2025 and 2055: Annualized over 2010–2110
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline.

	Scenario: Quantities in 2025—Quantities in 2055 in Tg CO_2 per Year Above Baseline		
	T-375-375	**T-375-900**	**T-375-0**
Annualized (2010–2110)			
Afforestation	18	23	2
Forest management	62	70	9
Agricultural soil carbon sequestration	88	79	54
Fossil fuel mitigation from crop production	35	38	4
Agricultural CH_4 and N_2O mitigation	16	20	5
Biofuel offsets	21	200	0
All Activities	240	429	75
Marginal Cost per t CO_2 Eq. Year 2000 $	$23.38	$26.10	$14.76

Figure 5 1: Least Cost Mitigation Quantities by Scenario and Activity in 2025 and 2055
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over 2010 2110.



price scenarios in Chapter 4, the other four major activities also make substantive contributions, leading to a diverse portfolio of options.

- **When the quantity is raised from 375 Tg/year in 2025 to 900 Tg/year in 2055, the role of biofuels emerges as a dominant strategy.** In this much larger level of activity emphasizing longer-term mitigation, biofuels account for almost one-half the annualized total GHG mitigation.
- **When the 375 Tg/year mitigation quantity level is completely relaxed after 2025, the policy's effectiveness is substantially undermined.** It produces less than one-third the

annualized mitigation of the constant 375 Tg quantity (T-375-375) and less than 20 percent of the T-375-900 scenario quantity.

- **Agricultural soil carbon sequestration and forest management are key options in all three scenarios.** Agricultural soil sequestration is the first or second contributing activity in all three scenarios, and forest management is second or third in all three.
- **Afforestation makes little contribution to the mitigation totals under any of the national mitigation quantity scenarios.** Although afforestation is a key strategy at the middle to upper prices in the GHG pricing scenarios of Chapter 4, the other options are more cost-effective ways to achieve the fairly modest national mitigation levels assessed here. Afforestation is an effective strategy for a more aggressive effort to achieve higher mitigation totals at higher cost per unit mitigated.
- **The marginal cost ranges from about \$15 to \$26 per tonne CO_2 Eq., depending on the stringency of the mitigation scenario.** The marginal cost per tonne is about the same for the scenarios where the mitigation goal stays the same or rises in the second period (to 2055) but is about half that amount for the scenario that has no goal after 2025. The marginal cost of an additional tonne of mitigation measures the net cost of an additional unit being added to the GHG mitigation quantity.[1] In essence, this suggests that additional mitigation could be warranted if the marginal benefits exceed these levels.

The summary results of Table 5-2 could mask important variations in sectoral mitigation over time. These timing patterns are illustrated in Figure 5-2, which shows cumulative mitigation totals over time under the three quantity scenarios, and in Table 5-3, which reports annual totals by activity for three key years: 2015, 2025, and 2055. The patterns demonstrate that the establishment of fixed and finite-lived mitigation levels can induce undesirable consequences before the quantity goal takes effect and after the mitigation quantity is no longer in place, as described below.

Recall that in each case, the annual mitigation quantity does not come into effect until 2025. Therefore, all action in the first decade (2010–2020) is unrestricted. As a result of this delay, two phenomena are projected. First, emissions of CO_2 and non-CO_2 gases are not much affected in the first decade, because there is no incentive to achieve these reductions until later. Second, the sequestration activities reflect anticipatory behavior. The net level of annual sequestration in 2015 is lower under the national quantity scenarios than under the baseline, as reflected by the negative values in Figure 5-2 and Table 5-3. In other words, the 2025 mitigation quantity goal induces carbon release in the preceding decade.

The early induced carbon releases are especially pronounced for forest management, where relatively large carbon reductions are projected in the decade preceding the mitigation quantity level taking effect in 2025. This pattern implies a reaction by forest owners to reduce carbon stocks before the target takes effect through some combination of higher harvests or reduced management. This may be a reaction to preempt some of the opportunity costs placed on harvests when the fixed levels take effect in 2025. Nonetheless, it suggests that a national mitigation quantity set to take effect a decade or more in the future could produce some short-run unintended negative consequences if not designed carefully.

The unintended consequences can extend beyond the time period as well. For the one scenario in which the national quantity level is not kept in place after 2025, net sequestration levels drop below the baseline for each of the forest and agriculture sequestration options. Without a continuing mitigation quantity to shoot for, landowners have little incentive to keep carbon stocks above baseline levels.

[1] The cost to consumers and producers is measured as the aggregate sum of producer and consumer surplus in the forest and agriculture sectors. This is commonly referred to as the "social welfare cost" of a market intervention.

Figure 5 2: Scenarios with Objective of Mitigating: (a) 375 Tg CO_2 Eq. in 2025 and Maintaining; (b) 375 in 2025 and 900 Tg CO_2 Eq. in 2055; and (c) 375 Tg CO_2 Eq. in 2025 without Maintaining Thereafter

Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline to 2110.
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline to 2110.
Note: Scale varies for each graph, from 4,000 to 70,000 Tg CO_2.

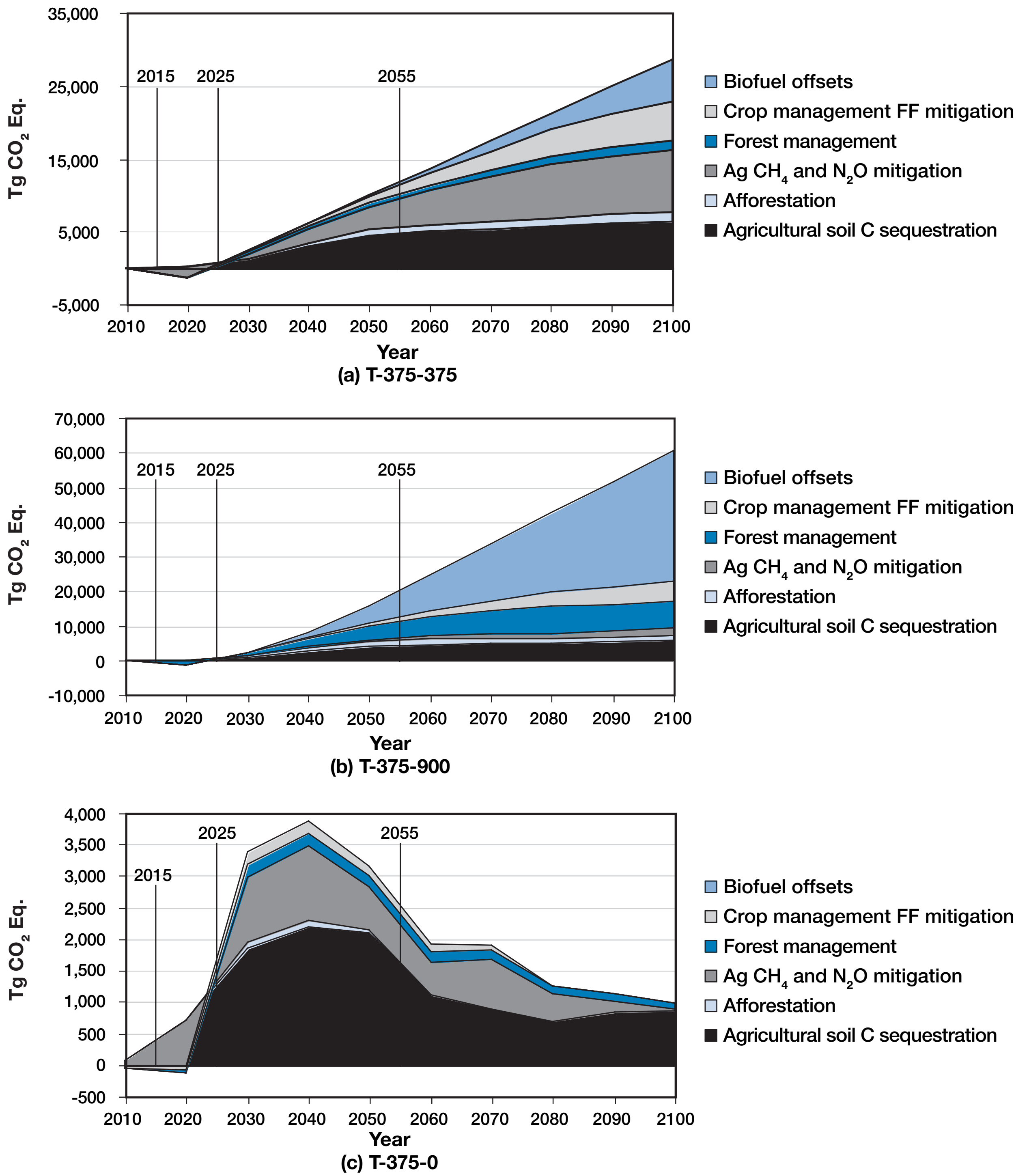


Table 5-3: Least-Cost Mitigation Response to Fixed National GHG Mitigation Levels in 2015, 2025, and 2055
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline.

	Scenario: Quantities in 2025—Quantities in 2055 in Tg CO_2 per Year Above Baseline		
Year	**T-375-375**	**T-375-900**	**T-375-0**
2015 (midpoint of 2010 decade)			
Afforestation	8	9	1
Forest management[a]	–180	–192	–105
Agricultural soil carbon sequestration	–6	–18	58
Fossil fuel mitigation from crop production	4	1	3
Agricultural CH_4 and N_2O mitigation	5	3	3
Biofuel offsets	0	0	0
All Activities	–170	–198	–41
2025 (midpoint of 2020 decade)			
Afforestation	17	20	9
Forest management	234	230	207
Agricultural soil carbon sequestration	87	85	124
Fossil fuel mitigation from crop production	18	19	17
Agricultural CH_4 and N_2O mitigation	19	20	17
Biofuel offsets	0	0	0
All Activities	375	375	375
2055 (midpoint of 2050 decade)			
Afforestation	3	33	–13
Forest management	161	184	–22
Agricultural soil carbon sequestration	66	51	–99
Fossil fuel mitigation from crop production	59	69	–3
Agricultural CH_4 and N_2O mitigation	20	27	–2
Biofuel offsets	66	536	0
All Activities	375	900	–139

[a] Positive values indicate mitigation or reductions in net emissions below baseline levels. Negative values indicate an increase in net emissions above baseline levels. Net emission increases are possible when the desired mitigation levels are not in effect, such as in 2015, and after 2025 under T 375-0.

Regional Activity Contributions to National Mitigation Levels

The top 10 region/activity combinations that could contribute to the national mitigation quantity scenarios are presented in Table 5-4.[2] The region-activity rankings for the $15/tonne CO_2 Eq. constant price scenario from Chapter 4 are also listed in Table 5-4 for comparison.

For the two scenarios with mitigation quantity levels continuing beyond 2025, a diverse mix of activities and regions comprises the mitigation portfolio. For the T-375-375 scenario, the top 10 opportunities are spread across eight regions and across all but one of the activities.

The regional diversity narrows some when the 2055 quantity is set at 900 Tg CO_2 per year, because

Table 5-4: GHG Mitigation Quantity Ranking by Region/Activity Combination: Fixed National Mitigation Quantity Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized 2010–2110.

		Scenarios							
		T-375-375		T-375-900		T-375-0		Constant $15 GHG Price	
Region[a]	Activities	Rank	GHG Quantity	Rank	GHG Quantity	Rank	GHG Quantity	Rank	GHG Quantity
CB	Agricultural soil carbon sequestration	1	35.6	4	39.3	1	20.8	4	62.2
SE	Forest management	2	33.9	3	39.9	3	10.4	3	69.2
LS	Agricultural soil carbon sequestration	3	31.3	5	31.6	2	15.2	6	36.9
SC	Fossil fuel mitigation from crop production	4	17.4	7	16.9			8	23.7
NE	Biofuel offsets	5	13.8	1	121.7			5	47.9
SC	Forest management	6	12.0	8	13.5			1	127.7
RM	Afforestation	7	11.8	9	11.8			9	11.7
SW	Fossil fuel mitigation from crop production	8	8.8	10	8.8				
NE	Forest management	9	7.0						
GP	Agricultural soil carbon sequestration	10	6.8			4	6.8	7	29.3
RM	Agricultural soil carbon sequestration					5	3.8		
NE	Agricultural soil carbon sequestration					9	1.6		
SW	Agricultural soil carbon sequestration					6	3.6	10	10.5
CB	Afforestation					7	2.0		
SE	Biofuel offsets			2	49.3				
SC	Biofuel offsets			6	28.8				
RM	Agricultural CH_4 and N_2O mitigation					8	1.9		
SC	Agricultural CH_4 and N_2O mitigation					10	1.5		
SC	Afforestation							2	115.8

[a] See Table 3-2 in Chapter 3 for region key.

[2] Consult Chapter 3, Table 3-2, for a key of the regions tracked by the FASOMGHG model.

5 of the top 10 opportunities occur in the two southern regions. And agricultural soil carbon sequestration is the dominant strategy for the T-375-0 scenario, reflecting the short-term nature of the scenario. Non-CO_2 mitigation is part of the top 10 set in the T-375-0 scenario only.

National Mitigation Quantity Scenarios Summary

Taken together, the three national quantity scenarios provide insights into the importance of timing in implementing mitigation options. First, one sees that delaying *the achievement of a specific national mitigation quantity a decade or more can induce some emitting activity in the short term.* This occurs primarily with the sequestration options, where carbon stock dynamics inextricably link actions and carbon consequences across decades. Therefore, setting a future mitigation goal directly affects land use and management decisions today.

However, the early reductions in sequestration found in the model simulations occur, in part, because these particular scenarios were designed to achieve *annual* mitigation quantities, relative to a future baseline. If, instead, the scenario was set to maintain a certain level of carbon *stock* in the future and this stock was higher than the stock that exists at the time such a goal is announced, then the incentive to reduce carbon stocks prior to the scenario date would be effectively eliminated. *Aiming for cumulative rather than annual mitigation quantities could potentially avoid these early period unintended consequences.*

GHG benefits are likely to be reversed if the desired mitigation level is not maintained. But a more permanent enhancement in forest and agricultural carbon storage and emissions reduction would require a sustained commitment to achieve these levels.

Limiting Payments by GHG Type

The analyses to this point have considered all major GHGs in forestry and agriculture (CO_2, CH_4, and N_2O) to be subject to mitigation incentives. However, much of the focus in climate change mitigation has been on CO_2, whose emissions constitute a majority of the aggregate anthropogenic global warming potential, especially in the United States. Therefore, we consider the consequences of focusing incentives on emissions and sequestration of CO_2 only. This is particularly interesting for the agriculture sector, a major source of non-CO_2 emissions that could be perversely affected by a CO_2-only policy, if it led to increases in agricultural non-CO_2 GHGs.

Paying for CO_2 Only vs. Paying for All GHGs: \$15/t CO_2 Eq.

To evaluate the CO_2-only option, the FASOMGHG model was run with a price of \$15/t CO_2 Eq. for CO_2 emissions and sequestration and a price of zero for the other GHGs tracked by the model. Results of this scenario are compared to the results when all GHGs are paid \$15 per tonne CO_2 Eq. as illustrated in Table 5-5.

Table 5-5: Mitigation Quantities: Payments for CO_2 Only vs. Payment for All GHGs (\$15 per t CO_2 Eq.)
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized 2010–2110. Net emissions include non-CO_2 gases (even though payments are for CO_2 only).

Activity	CO_2 Only	All GHGs
Afforestation	110	137
Forest management	216	219
Agricultural soil carbon sequestration	176	168
Fossil fuel mitigation from crop production	49	53
Agricultural CH_4 and N_2O mitigation	21	32
Biofuel offsets	42	57
All Activities	613	667

The results in Table 5-5 represent annualized totals for the entire projection period and can be summarized as follows:

- Limiting payments to CO_2 only reduces total mitigation potential by about 54 Tg/year or about 8 percent below the mitigation obtained when all GHGs are priced.

- CO_2 and non-CO_2 mitigation are largely complementary:
  - About two-thirds of the non-CO_2 mitigation can be accomplished while paying for CO_2 only.
  - CO_2 mitigation (e.g., especially afforestation and biofuels) is enhanced when non-CO_2 gases are included in the payment approach ("all GHGs"), suggesting that non-CO_2 reduction incentives divert land from traditional agriculture to these activities.
  - Only agricultural soil carbon sequestration shows a (slight) trade-off between CO_2 and non-CO_2 payments (i.e., the amount of agricultural soil carbon sequestered declines very slightly when all GHGs are subject to payment, rather than just CO_2).

The complementarity between CO_2 and non-CO_2 mitigation is a potentially important factor when considering incentives for mitigation. First, it implies that much of the non-CO_2 mitigation can be achieved without explicitly providing incentives to reduce non-CO_2 gases. Second, it implies that including the non-CO_2 reduction activities has synergistic benefits in CO_2 reductions.

CO_2 Only: Mitigation Over Time

To illustrate mitigation over time, Table 5-6 presents the mitigation results for CO_2-only payment by activity for the key years of 2015, 2025, and 2055, and Figure 5-3 shows cumulative mitigation totals for the CO_2-only and all GHG payment options for the entire projection period.

The temporal patterns shown in Table 5-6 and Figure 5-3 reinforce results presented earlier, namely that *forest and agricultural sequestration options generate sizeable quantities of mitigation in the first couple of decades after implementation, but these effects diminish and even reverse in the out years.* Also, as seen previously, the biofuel option does not take hold for several decades. Figure 5-3 shows that including non-CO_2 GHGs for payment increases the cumulative mitigation over time but does not alter the saturation and reversal pattern very much, because that pattern is driven entirely by the (CO_2) sequestration activity dynamics.

Selected Activity Scenarios

A project-based approach to mitigation is one in which specific GHG-mitigating activities are undertaken in distinct locations. One characteristic of project-based approaches is that their scope is generally limited—some activities are eligible

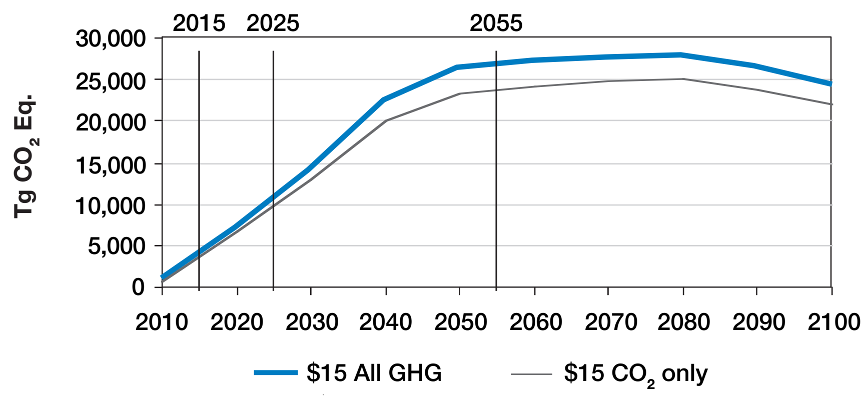
Table 5-6: National GHG Mitigation Totals in Key Years by Activity: Payment for CO_2 Only at \$15/t CO_2 Eq. (Includes Non-CO_2 GHGs)
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline.

	Year[a]		
Activity	**2015**	**2025**	**2055**
Afforestation	132	206	–180
Forest management	226	160	140
Agricultural soil carbon sequestration	201	209	–2
Fossil fuel mitigation from crop production	26	30	57
Agricultural CH_4 and N_2O mitigation	17	22	17
Biofuel offsets	0	0	56
All Activities	601	627	88

[a] Years represent midpoint of model decades 2010, 2020, and 2050, respectively.

Figure 5 3: Cumulative Mitigation: Payment for CO_2 Only (Includes Non CO_2 GHGs) vs. All GHGs at $15/t CO_2 Eq.

Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.



for GHG payments and others are not. Therefore, it is useful to evaluate the effects of a GHG incentive approach that targets its payments to a selected set of activities—to see the effect on the sectors' aggregate mitigation potential, and whether limiting eligible activities causes unintended consequences.

GHG mitigation projects can be seen as part of a broad set of landowner incentive programs administered by federal or state governments. There is a long history of these types of programs at the federal level over the last 50 years. Examples include the experiences of the Soil Bank Program, the Forestry Incentives Program (FIP), CRP, Wetlands Reserve Program (WRP), and various components of Farm Bill legislation including, of late, specific provisions to enhance carbon sequestration in forestry and agriculture.

To assess such mitigation activity at a smaller scale, five hypothetical scenarios are defined in Table 5-7. In each scenario, only one or a small number of activities receive GHG payments. All other activities within the forest and agriculture sectors face no price and thus receive no reward or penalty for changes in net GHG emissions.

The focus of these scenarios is on activities that (a) have large potential effects at low prices, as demonstrated in the results of Chapter 4 (e.g., agricultural soil carbon sequestration, forest management); (b) are easier to monitor because they involve a discrete land-use change (afforestation); or (c) are tied to other closely monitored market transactions (e.g., biofuels). Although three of the five scenarios pay for just a single activity, the other two separately evaluate payments for a somewhat wider range of forest and agricultural management activities.

Table 5-7: Selected Activity Scenarios

Activities Subject to Payments
Afforestation
Afforestation + forest management
Biofuels
Agricultural management (agricultural soil carbon + agricultural CH_4 and N_2O + crop management fossil fuels)
Agricultural soil carbon

Each scenario is evaluated at one of three price levels ($/t CO_2 Eq.) previously evaluated in Chapter 4:

- $15, constant over time;
- $3, rising at 1.5 percent per year; and
- $3, rising at 4 percent per year, capped at $30.

National Results

Results of the selected payment simulations are summarized in Table 5-8. This table shows the annual mitigation totals in key years (2015, 2025, 2055) for each of the specific activities under each of the price scenarios. The general patterns across the activities are similar to those found under these same price scenarios in Chapter 4 (where payments were comprehensively applied to all activities). Agricultural mitigation, specifically agricultural soil carbon sequestration, is the primary option at the lowest prices ($3, rising at 1.5 percent), forest carbon sequestration assumes a large role when prices are somewhat higher ($15, constant), and biofuels are a key strategy when GHG prices are expected to rise substantially in the future ($3, rising at 4 percent per year).

Regional Results

Each of the activities evaluated here has a unique geographic distribution of mitigation opportunities in response to the activity-specific GHG payments. The set of eligible activities, and landowner response to GHG price signals, for a given mitigation incentive is unlikely to be evenly distributed across regions. The regional implications and distribution are discussed for each activity below.

Payments for Afforestation Only

The $15/t CO_2 Eq. scenario is the only one of the three evaluated price scenarios showing much afforestation occurring at all. Under this scenario, afforestation is concentrated almost entirely in the South-Central United States (99 percent of total), with very small amounts in the Rocky Mountain and Pacific Northwest regions. Thus, under the type of targeted afforestation evaluated here, efforts could be concentrated regionally in the southern United States, which is where much of the nation's afforestation and reforestation are occurring at the present time. Under a more aggressive policy with higher prices, other regions would be drawn in as land is competed away from otherwise more profitable alternatives.

Payments for Afforestation + Forest Management Only

When forest management is combined with afforestation for targeted payments, this simulates the effect of full forest carbon incentives. As shown in Figure 5-4, this broadening of the incentives brings in contributions from other regions, for example, the Pacific Northwest, Westside, and Northeast. The predominant expansion, however, is into the Southeast United States, which

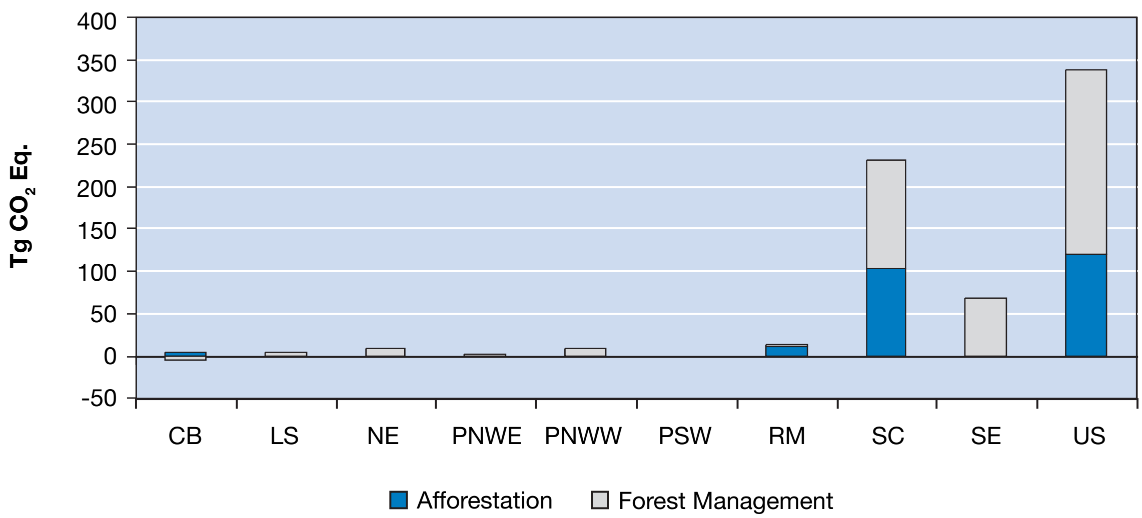
Table 5-8: GHG Mitigation under Payment for Specific Activity Scenarios
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for key years: 2015, 2025, and 2055.

	GHG Price ($/t CO_2 Eq.)								
	$15			$3 @ 1.5%			$3 @ 4%		
Activity Paid for	**2015**	**2025**	**2055**	**2015**	**2025**	**2055**	**2015**	**2025**	**2055**
Afforestation	89	288	–173	0	0	–15[a]	0	0	38
Afforestation + forest management	350	366	–87	61	25	15	69	–58	162
Biofuels	0	0	237	0	0	0	0	0	352
Agricultural management	244	242	33	113	129	51	25	58	176
Agricultural soil carbon	191	184	–39	77	93	7	–5	16	143

Note: Scenarios are not additive because some overlap (e.g., afforestation and forest management).

[a] Carbon losses from afforestation in 2055 reflect harvesting of forests planted between 2025 and 2055 in this scenario.

Figure 5 4: GHG Mitigation under Payments for Afforestation and Forest Management Only at $15/t CO_2 Eq.: By Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized 2010 2110.



generates about 70 Tg CO_2 per year of additional carbon sequestration through forest management. The South-Central and Southeast regions together contribute about 90 percent of the total mitigation opportunities in the combined forest carbon scenario, thereby suggesting a fairly concentrated regional response to forest mitigation opportunities. This is not surprising given the southern states' large private timberland base and position as the nation's largest producer of timber and forest products.

Payment for Biofuels Only

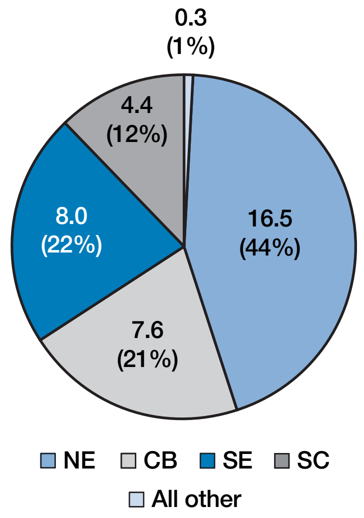
Consider two points raised in previous chapters about biofuel adoption: (1) adoption is only economic at prices of $15/t CO_2 Eq. and above and (2) biofuel demand is assumed to be capacity constrained in the short run, based on data from the EIA (Haq 2002). As a consequence, it is not surprising to find that $3 rising at 4 percent generates the largest targeted response from biofuel production of the three price scenarios evaluated. After about 40 years, the rising price exceeds $15, and biofuel use capacity is expected to grow throughout the century (see the biofuel demand assumptions referenced in Chapter 4). Together this implies that the capacity expands enough in time to take advantage of the higher prices. In contrast, the $15 per tonne constant price attracts some biofuel adoption over time, but the incentive does not get stronger as demand constraints relax. And the $3 per tonne price rising at 1.5 percent per year is insufficient to draw biofuel production even in the longer run.

The regional distribution of biofuel production/mitigation under this price scenario (Figure 5-5) is a bit wider than the regional distribution of forest mitigation opportunities, but the concentration is still entirely within the eastern United States.[3] The Northeast and Corn Belt regions together comprise about two-thirds of the biofuels opportunity, with almost all of the remainder in the South-Central and Southeast regions.

[3] Note that Figure 5-5 expresses mitigation quantities as cumulative totals over the entire projection period (2010–2110) rather than annualized totals. This is done because the discounting and annualization approach presented in Chapter 4 is not applicable under rising-price scenarios (see Herzog et al. 2003).

Figure 5 5: GHG Mitigation under Payments for Biofuel Offsets Only at \$3/t CO_2 Eq., Rising at 4 Percent per Year, By Region

Quantities are cumulative mitigation (2010 2110) in petagrams (billion tonnes) CO_2 Eq.

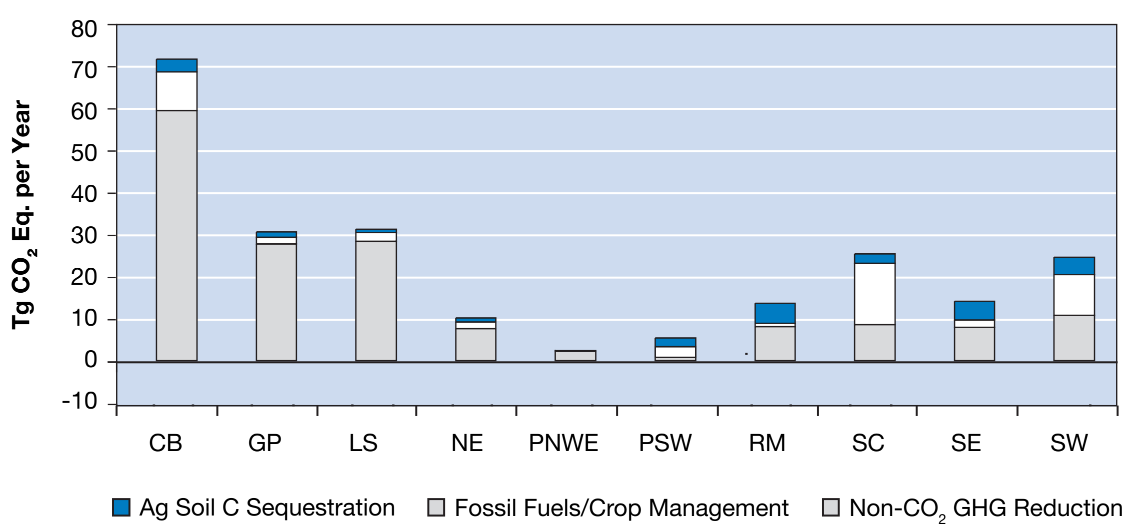


Payments for Agricultural Management Only

The agricultural management scenario targets payments for soil carbon sequestration, fossil fuel (CO_2) reductions for crop management practices, and non-CO_2 emission reductions through changes in crop and livestock management. In Figure 5-6, the regional distribution of these activities is depicted under the \$15/t CO_2 Eq. constant-price scenario.

The scenario shows that the mitigation activities are widely distributed across the 10 main agricultural regions in the United States. Much of the mitigation is the result of agricultural soil carbon sequestration practices in the Corn Belt, Lake States, and Great Plains. There is also a modest amount of mitigation through reductions in fossil fuel emissions through crop practices in the South-central and Southwest United States. Non-CO_2 reductions are small, relative to the CO_2 options, but comprise a material share of the

Figure 5 6: GHG Mitigation by Region and Activity under Payments for Agricultural Management Only: \$15/t CO_2 Eq.
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized 2010 2110.

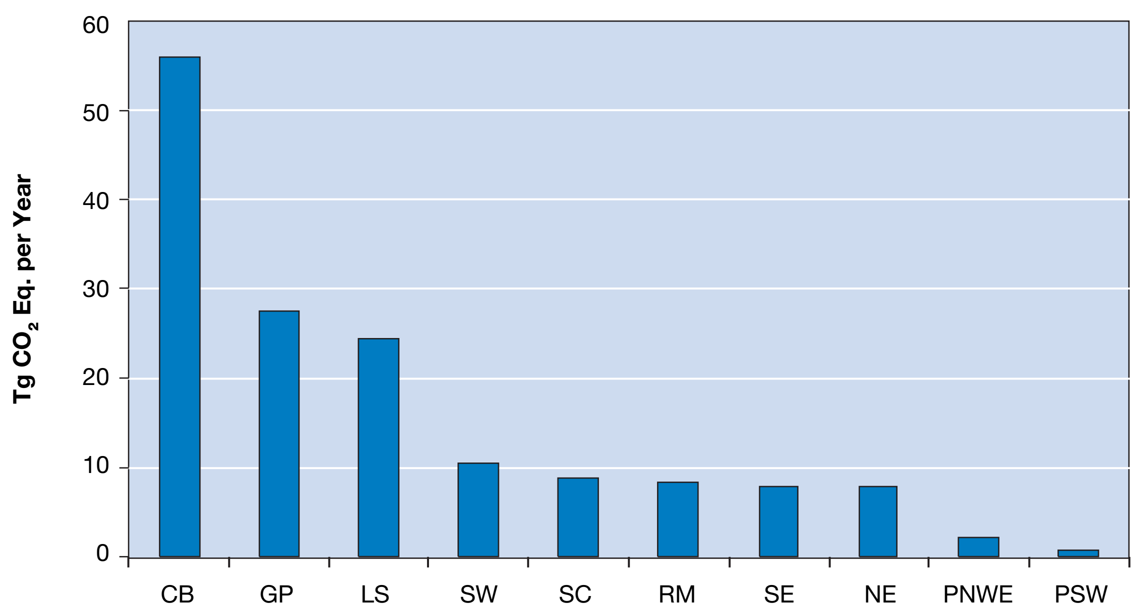


mitigation totals in the Southeast, Southwest, Rocky Mountains, and Corn Belt.

Payments for Agricultural Soil Carbon Sequestration Only

The regional distribution of mitigation under the agricultural soil carbon-only payment scenario for the \$15/t CO_2 Eq. constant-price scenario is illustrated in Figure 5-7. Landowner responses to the price incentives are distributed across all agricultural regions, with the Corn Belt generating the most annual soil carbon sequestration (56 Tg CO_2 Eq. per year), followed by the Great Plains (27 Tg) and Lake States (24 Tg). On the other end of the spectrum, there is virtually no soil carbon response (less than 3 Tg CO_2 Eq. per year) in the Pacific Northwest and Pacific Southwest because of biophysical and economic factors impeding adoption in those regions at the price trajectory evaluated. The remaining five regions generate a modest amount of sequestration in response to the incentive (between 8 and 11 Tg per year).

Figure 5 7: Regional Distribution of Soil Carbon Sequestration under Payment for Soil Carbon Only: \$15/t CO_2 Eq. Constant Price
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized 2010 2110.



CHAPTER 6

Implications of Mitigation via Selected Activities

Chapter 6 Summary

GHG mitigation activities may include project-based approaches (i.e., activity- and location-specific mitigation actions). Project-based GHG accounting can be used to ensure that the GHG mitigation attributed to a project reflects its net GHG reductions over time by including baseline GHG effects that would have occurred without project intervention, reversal of any carbon sequestered over time, and any leakage of GHG emissions outside project boundaries. Leakage effects are found to be more or less confined to the forest sector. The pay-for-afforestation-only scenario shows leakage of almost 25 percent, whereas leakage appears minimal if all forest carbon management activities receive payment. Leakage rates vary regionally and over time because of market responses and forest carbon dynamics. Most leakage due to targeted afforestation occurs within the first 2 decades. The broader the spatial scale in which market leakage is evaluated for an activity that produces commodities traded in that market, the higher the leakage estimated.

Leakage from individual activities in the agriculture sector appears to be small, roughly 0 to 5 percent in this analysis. Paying for additional sequestration through per-tonne CO_2 payments is more efficient than paying on a per-acre basis. Per-acre payments can be made more efficient (i.e., more closely match the efficiency of per-tonne CO_2 payments) through adjustments based on the land's carbon productivity potential.

As discussed in Chapter 5, it seems unlikely for a variety of reasons that fixed limits would be placed on GHG emissions from forestry and agriculture. Rather, selected opportunities for mitigation within these sectors may be seen as an effective means to offset GHG emissions elsewhere. As a result, the scope of eligible mitigation activities, GHGs, and land coverage within these sectors may be limited. For the purposes of this report, these activity- and location-specific GHG mitigation actions are called projects, referring to the actions the landowner takes on a specific tract of land to mitigate GHGs. For example, an individual farmer engaged in a tree-planting activity for the purposes of sequestering carbon would constitute a project. This chapter examines how limiting the scope and coverage of mitigation actions to project-based actions can affect the magnitude and distribution of GHG mitigation within the agricultural and forest sectors.

Observers have noted a number of important factors related to implementing these project-based approaches (CCBA 2004; IPCC 2000):

- demonstrating and quantifying net benefits,
- arranging and paying for the transactions, and
- ensuring sustainable development objectives are met.

The chapter continues with the discussion of several key technical issues related to quantifying GHG benefits, including *leakage, baseline-setting, and permanence or the potential reversibility of GHG* *benefits*. Other project-relevant factors include measurement, monitoring, and verification (MMV) of emission reductions or sequestration and assembly or aggregation of these quantified GHG benefits across market or program participants. MMV and assembly can impose transaction costs that should be considered when evaluating the economic attractiveness of mitigation projects. These issues are all discussed in more detail in the section that follows.

Because it is an aggregate model operating at regional resolution, FASOMGHG does not directly model implementation of activity at the individual project level. However, the model is flexible enough to limit the scope of incentives to subsets of activities, regions, and GHGs, thereby providing some insight into the effect of such limitations on mitigation potential. For instance, FASOMGHG is used in this chapter to estimate leakage potential when GHG incentives are confined to a subset of activities. In addition, the chapter includes an empirical analysis of modifying how incentives are provided to assess GHG payments on a per-acre, rather than per-tonne (t CO_2), basis (the approach thus far). Per-acre payments have been discussed as a means to economize on MMV and transaction costs (Antle et al. 2003).

The next section further discusses project-level implementation issues and the extent to which these factors can affect a project's net GHG benefits.

Project Quantification Issues and Costs

Project-based GHG mitigation activities are typically defined as those with clearly defined geographic boundaries, time frames, and institutional frameworks (IPCC 2000, Chapter 5). Certain characteristics of forestry and agricultural project activities can complicate the estimation of their net GHG mitigation benefits. Methods to address these concerns are discussed below.

Quantifying the Net GHG Contribution of Projects

One challenge with project-based approaches is ensuring that the amount of mitigation attributed to a particular project reflects the net contribution of that project to GHG reductions over time. Of particular importance is the notion that the GHG accounting captures

- the (baseline) GHG effects that would have occurred without the project intervention;
- the reversal or re-release of any carbon sequestered over time through harvesting, discontinuation of practices, or natural disturbance; and
- any leakage of GHG emissions that may have occurred outside the boundaries of the project.

Each of these issues is addressed below. Special emphasis is placed on the leakage issue because FASOMGHG model simulations in this report, in addition to other recent studies, are able to quantify leakage effects from activity-specific incentive programs.

Establishing Project Baselines

The net GHG benefit of mitigation at the project scale can be estimated as the additional GHG emission reductions (sequestration) that occur relative to emissions (sequestration) levels in the project's absence. This is the concept of additionality. To determine *additionality*, one can estimate what would happen under business-as-usual or BAU without the project, which is referred to as the project *baseline* (IPCC [2000], Chapter 5).

A number of analyses and existing GHG mitigation programs have focused on the primacy and complexity of setting a baseline case to estimate GHG mitigation benefits (e.g., IPCC [2000], Chapter 5). Demonstrating additionality requires establishing a project baseline. In the case of GHG emission reduction projects in sectors such as electricity generation, a baseline might reflect the GHG emission rate that would prevail if the electricity were generated using standard technologies and fuels for a given sector and region. In forest- or agricultural-sector projects, however, it is a bit more complicated. First, an estimation of the land-use practices that would occur under BAU may be required. This may require using historical data on land use and management practices to provide an empirical foundation for BAU. The emergence of remotely sensed land-use data in a digitized format expands the possibilities for more complex and rigorous analysis of baseline land-use behavior. Then, once the land-use or management practice baseline is determined, estimation of what the emissions or sequestration rate would be under each of the BAU land-use practices can complete the baseline quantification.

No generally agreed methodology yet exists in the United States or internationally for project baseline setting by activity and region, although numerous efforts are under way to develop consistent protocols (CCBA 2004). It is beyond the scope of this report to assess project-level baseline options. Those methods are still largely in the proposal and evaluation stages. However, the development of project baselines is a cost of project development that is not directly captured in the economic analysis herein. This and other potential project transaction costs are addressed further below.

The focus of the discussion in this section has been on baselines at the *project level*, but sector-level baselines also are used in the broader analyses presented in Chapters 4 and 5. All mitigation results in the report are presented relative to the FASOMGHG sector baselines for forestry and agriculture. Thus, they are consistent with the concept of additionality discussed here. However, the model scenarios in those chapters do *not* impose additionality as a requirement for GHG payment—in essence all GHG effects are potentially eligible for payment.

Duration and Potential Reversal of GHG Benefits (Permanence)

As discussed throughout this report, GHG mitigation in the forest and agriculture sectors is susceptible to reversal. This is particularly relevant when carbon is sequestered for some time and then re-released accidentally (e.g., through wildfire) or as part of a planned intervention such as harvesting or land-use change. A complete accounting framework would capture both GHG releases to and GHG removals (sequestration) from the atmosphere. The FASOMGHG model scenarios presented in this report do capture such carbon losses from intentional releases tied to the harvesting and land-use decisions embedded in the model. Accidental carbon releases through fire, insects, and diseases are captured in the model via the biophysical yield functions used for forestry and agriculture, which are generally based on average yields, and therefore implicitly capture the persistent accidental losses from ambient sources.

However, a number of logistical factors may make such a complete accounting of GHG releases and removals over time as modeled in FASOMGHG for this report difficult for individual forestry and agriculture projects. These factors revolve around two key questions: (1) how does a set of mitigation activities or individual projects address the risk of reversal of GHG benefits during the lifetime of the program, and (2) how does it address this risk of reversal once the program or project has ended? Specific factors to consider include the following:

- Natural disturbance and other *force majeure* effects occur with uncertainty.
- Catastrophic loss of carbon could cause catastrophic financial losses for an investor.
- Project contracts generally have finite lives.

The first two factors relate to the difficulty of dealing with the risks of release when the project is under way. The unpredictability of project risk complicates project planning and decisions on actions that might be taken to reduce risks. By and large, the prospect that the investor might suffer catastrophic loss of the asset—carbon benefits, plus the normal accompanying economic asset, such as timber—makes the investment more risky and therefore reduces its attractiveness. If the risks are large enough, investors may seek ways to cover these potential losses if they proceed with the investment. Specific instruments for covering these risks (insurance policies, pooling projects with similar or dissimilar characteristics, holding some achieved mitigation benefits in reserve) might be considered, although the markets for these financial instruments may be a bit thin at this time (Subak 2003).

The other critical issue is that the project will typically involve a contract that expires after some period of time. The question then arises: how do you account for risks of release after a project ends? Various parties have proposed contractual options to address the risk of reversal in (primarily) carbon sequestration projects. These options are described in Table 6-1.

The options in Table 6-1 address how to account for reversal when it occurs. But project developers may also want to consider the actions they can take to minimize the risk of GHG reversal at the project design stage. One approach is to develop a carbon reversibility management plan, which lays out steps for identifying reversal risks, evaluating options for minimizing these risks, developing liability or compensation for risk when it occurs, and monitoring risks over the life of the project (WRI-WBCSD 2003).

Analytic consideration of project reversibility is outside the scope of this analysis and remains a topic of continued dialog and research.

Assessing the Potential for Leakage

Project-based mitigation approaches run the risk that some of the direct GHG benefits of these efforts will be undercut by leakage of emissions outside the boundaries of the project. IPCC (2000) defines leakage as "the unanticipated decrease or increase in GHG benefits outside of the project's accounting boundary (the boundary defined for the purpose of estimating the project's net GHG impact) as a result of project activities." The notion that project-based mitigation can generate leakage is a widely accepted concept.

Table 6-1: Candidate Approaches for Accounting for Reversal Risk from Carbon-Based GHG Mitigation Projects

Approach	Description	Sources
Comprehensive accounting		
Pay-as-you-go *Used in this report with FASOMGHG model*	Accounts for both carbon storage and carbon release to the atmosphere. This approach is consistent with national GHG inventory accounting practices. Addresses reversal as long as activity is reported in continuous program, including reversal beyond the finite life of a project.	IPCC (1996, 2000); Feng et al. (2001)
Approaches to project reversal risk (if comprehensive accounting not used)		
Temporary crediting	Designed to account explicitly for the fact that sequestration projects may only yield temporary reductions in atmospheric CO_2 concentrations. Three general approaches: • expiring, or temporary, Certified Emission Reductions, or tCER; • carbon "rental"; and • carbon "leasing."	Colombian Ministry of the Environment (2000); Blanco and Forner (2000); Chomitz (2000); Marland et al. (2001) ; Moura Costa (1996); Dutschke (2001); Dutschke (2002)
Ex ante discounting	Directly estimate and account for predicted reversal through management, harvesting, etc., in determining sequestration tonnes assigned at the beginning of the project.	McCarl and Murray (2002); Lewandrowski et al. (2004)

The challenge is quantifying leakage attributable to a specific activity and location. Leakage is relevant for assessing the effectiveness of programs that target a subset of land-based activities such as afforestation, biofuels, or agricultural soil carbon sequestration, as in the case of the scenarios presented in Chapter 5. Therefore, it is important to recognize the potential for leakage and to develop methods to

- target or design projects or sets of mitigation activities to minimize leakage,
- monitor leakage after projects or sets of mitigation activities are implemented,
- quantify the magnitude of leakage when it exists, and
- take leakage into consideration when estimating net GHG benefits of activities.

There has been little quantification of leakage effects in the forest and agriculture sectors. Chomitz (2002) uses an analytical model to compare the potential for leakage from forestry projects to that from energy-sector projects. Chomitz shows that forestry projects are not systematically more prone to leakage than energy-sector ones, as some parties have argued.

The five selected activity scenarios presented in Chapter 5 provide a framework by which to estimate the extent of leakage from selected, noncomprehensive activity sets. In each case, only one activity or subset of activities receives GHG payments. The GHG mitigation from each activity is then quantified and presented as the direct benefits of a selected activity. Although payments may only be applied to a single activity or subset, the FASOMGHG model tracks GHG effects throughout the entire U.S. forest and agriculture sectors. Therefore, one can compare the direct GHG benefits of each set of targeted payments with the net GHG effects for the entire combined sectors to quantify if and to what extent the direct benefits are offset by leakage somewhere else in the system. Leakage is calculated as a percentage of the direct benefits, accordingly:

$$\text{Leakage percent} = \frac{\text{Indirect GHG emissions from nontargeted activity}}{\text{Direct GHG reductions from targeted activity}} \times 100.$$

As has been demonstrated throughout this report, GHG mitigation actions in forestry and agriculture generate variable levels of mitigation over time, particularly for the sequestration options. To capture these fluctuating GHG effects in a single measure of leakage for each activity, the GHG quantity terms in the numerator and denominator of the leakage equation are expressed in annualized equivalent values for the corresponding projection period, decades 2010 to 2110. The implications of choosing a shorter time horizon for leakage estimation are discussed further below.

Table 6-2 presents the corresponding leakage estimates for each of the selected activity scenarios, evaluated at a single GHG price of \$15/t CO_2 Eq.[1] for each of the FASOMGHG-selected activity scenarios from Chapter 5. The most significant finding is that only one of the activities, afforestation, generates appreciable amounts of leakage (24 percent).

Once afforestation and forest management are combined and targeted together, almost all of the leakage vanishes because essentially all of the leakage from mitigation incentives that induce afforestation occurs through carbon reductions from reduced forest management. This reduced forest management is caused by the corresponding decline in timber prices and incentive to invest in forest management caused by increasing the area of land in forests. When forest management is eligible to receive incentive payments, this leakage largely goes away. In fact, the leakage effect is even slightly *negative*, meaning that there is a small amount of "good" leakage (reduced net emissions) spilling out of the forest sector into the agriculture

[1] Leakage effects in Table 6-2 are presented for the \$15/tonne CO_2 Eq. price because that price induces some activity in all categories. The lower prices evaluated in Chapter 5 (\$3/tonne, rising at 1.5 percent and 4 percent per year) generate too little afforestation to discuss leakage effects for that activity.

sector, further augmenting the benefits of the direct payments for forest carbon. This good leakage occurs as the sectors reallocate land and management in response to the forest-sector incentives, and the reallocation of resources in agriculture leads to a slight decline in agricultural emissions (i.e., an increase in indirect mitigation). These leakage values are small in both absolute and percentage terms. Given the uncertainty involved in any complex modeling exercise as this, the more important message is that leakage appears minimal if all forest carbon activities are targeted for payment together. Likewise, the results in Table 6-2 suggest that leakage from payments targeting biofuels and agricultural activities is quite small, as well, roughly 0 to 6 percent.

The time horizon for GHG mitigation, particularly forest carbon sequestration, is long, with actions taken in one year having implications for many decades down the road. However, the time horizon for projects or sets of reported mitigation activities is likely to be shorter, confined by the institutional realities of changing policy priorities and of investment time frames. The discussion in Box 6-1 considers the implications of viewing leakage effects for an afforestation project from a shorter time frame than the 100-year projection period used to generate the leakage estimates in Table 6-2. It concludes that for the afforestation \$15/t CO_2 scenario reviewed, the leakage rate is unchanged from the 100-year value under a 50-year time frame of analysis. But it significantly increases under a 20-year time frame because most afforestation leakage occurs in the first few decades.

Leakage from Forest Carbon Sequestration: A Closer Examination

Because the results in Table 6-2 suggest leakage effects are more or less confined to the forest sector, we take a closer look at forest carbon leakage, further detailing the FASOMGHG results and drawing from other published forest carbon leakage estimates.

Focusing first on the leakage results from paying for afforestation only, the 137 Tg CO_2 per year of direct GHG benefits from afforestation is offset by leakage of about 33 Tg CO_2, or about 24 percent. Thus, the net GHG benefit is 104 Tg CO_2, when leakage is taken into account.

Table 6-2: Leakage Estimates by Mitigation Activity at a GHG Price of \$15/t CO_2 Eq.
All quantities are on an annualized basis for the time period 2010–2110.

Selected Mitigation Activities	A GHG Effects of Targeted Payment (Tg CO_2 Eq.)	B Net GHG Effects of All Activities (Tg CO_2 Eq.)	C Indirect GHG Effects from Nontargeted Activity[a] (Tg CO_2 Eq.)	D Leakage Rate[b] (%)
Afforestation only	137	104	–33	24.0
Afforestation + forest management	338	348	10	–2.8
Biofuels	84	83	–1	0.2
Agricultural management	230	231	1	–0.1
Agricultural soil carbon	154	145	–9	5.7

[a] Indirect effects: C = (B – A).

[b] Leakage rate: D = –(C/A) x 100; rounding occurs in table.

Note: Negative leakage rate in D refers to beneficial leakage (i.e., additional mitigation outside the selected activity region, also called positive leakage).

In what activities and regions can the leakage be found? Figure 6-1 provides some insights. As described in Chapter 5, virtually all of the afforestation response in the afforestation-only payment scenario occurs in the South-Central states (about 99 percent). This is depicted in the left side of Figure 6-1. The right side of Figure 6-1 shows the regional and activity nature of the leakage induced by the afforestation payments. The primary source of leakage is, as expected, from the decline in carbon from forest management. But Figure 6-1 shows two other nonforest leakage effects caused by the movement of land from agriculture to forests within the South-Central region. First, this land movement produces a decline in crop-related fossil fuel (CO_2) emissions within the region, which is

Box 6-1: Shortening the Time Horizon for Quantifying Leakage

The leakage estimates in Table 6-2 are calculated using the annualized values for the time stream of GHG mitigation effects over the entire FASOMGHG projection period, spanning the time period 2010 to 2110. These annualized values capture in one summary metric the entire projected mitigation profile over a long period of time. However, analysts also might be interested in confining measurement of leakage just to a set period of time pertinent to a given mitigation reporting framework (e.g., 2010) or the time frame of a given project. This may be particularly applicable to highly time-dynamic mitigation options such as afforestation. Therefore, we recalculate the leakage estimates for the afforestation scenario, confining the time period of observation to 5 decades and 2 decades, respectively, and ignoring all future GHG effects beyond that. The effect of the change in time horizon is reflected below for the $15/tonne CO_2 Eq. GHG price.

Targeted Mitigation Activity: Afforestation at $15/t CO_2 Eq.
All GHG quantities in the table are annualized over the time horizon indicated in far left column.

Leakage Time Horizon	A GHG Effects of Targeted Payment (Tg CO_2 Eq.)	B Net GHG Effects of All Activities (Tg CO_2 Eq.)	C Indirect GHG Effects from Nontargeted Activity[a] (Tg CO_2 Eq.)	D Leakage Rate[b] (%)
10 decades	137.4	104.4	–33.0	24.0%
5 decades	170.7	129.7	–41.0	24.0%
2 decades	208.5	127.7	–80.8	38.8%

[a] Indirect effects: C = (B – A).

[b] Leakage rate: D = –(C/A) x 100; rounding occurs in table.

Note: Negative indirect effects produce positive leakage rate.

Shortening the time horizon from 10 to 5 decades, while it affects the absolute annualized GHG mitigation quantities, does not affect the relative leakage rate. In essence, most of the important feedbacks between afforestation, forest management, and other activities are resolved in the first 5 decades.

However, when the time horizon is shortened to just 2 decades, both the absolute annualized mitigation values and the leakage rate are substantially affected. The leakage rate goes up because the initial response to an afforestation incentive payment is a decline in the area and intensity of managed forests not subject to the afforestation payments. This decline leads to a large drop in carbon on these other managed forests in the initial decades, which eventually evens out.

However, when the time horizon is confined to 2 decades, these initial declines in forest management carbon have a larger effect relative to the direct afforestation GHG benefits, which will continue to accumulate for several more years after the second decade.

This exercise suggests that most of the leakage effect from an afforestation project occurs in the first couple of decades. Therefore, if any project-level accounting standard chooses to ignore all carbon effects beyond the second decade, leakage effects will appear to be higher than their projected effect over a longer timeframe.

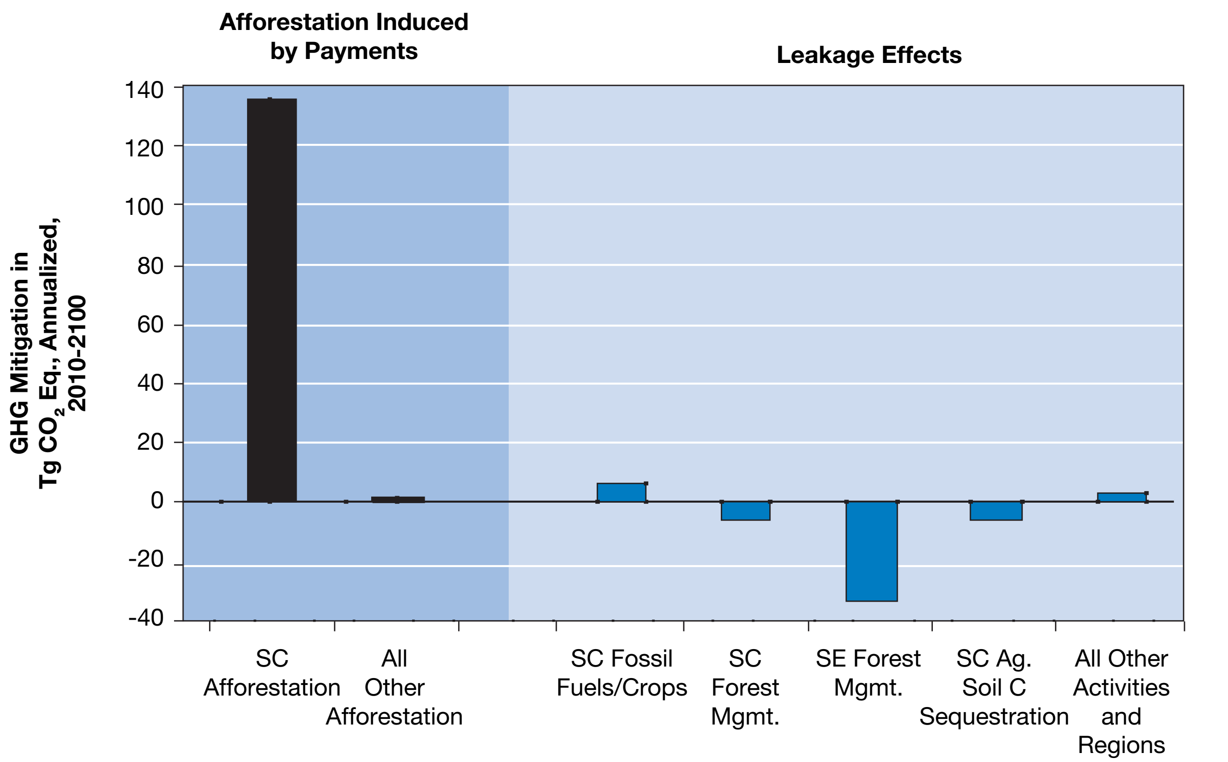
shown in Figure 6-1 as positive mitigation (i.e., "good" leakage). Second, this land movement reduces the South-Central cropland base and leads to more intensive cultivation practices, which increase soil carbon loss in the region (i.e., "bad" leakage).

The phenomena depicted in Figure 6-1 imply that this afforestation scenario, which turns out to be regionally confined to the South-Central United States for the scenario evaluated, has leakage effects that are also regionally confined. Virtually all of the leakage occurs within the two southern (South-Central and Southeast) regions. Most of the market feedback from this level of afforestation would have spatial limitations, because land-use change has localized tendencies. Forest management responses are confined to the South-Central and Southeast regions, because that is where most of the country's intensively managed forests are located.

Leakage Estimates from the Literature

A study by Murray, McCarl, and Lee (2004) uses FASOMGHG's precursor, the FASOM model, to estimate leakage from different U.S. forest carbon sequestration activities. Other than using the same basic modeling foundation, the Murray et al. study differs from this report in a number of ways. For example, the Murray et al. study includes scenarios for forest preservation and avoided deforestation in addition to afforestation but does not estimate leakage from agriculture or biofuel production.[2] That study also tries to simulate

Figure 6 1: Regional Leakage Flows for Afforestation Only Payment Scenario: \$15/t CO_2 Eq.



Note: Negative sign (e.g., South-Central Forest Mgmt.) is leakage, and positive sign is beneficial leakage (i.e., additional mitigation outside targeted activity region).

[2] Forest preservation refers to the withdrawal of existing forest from the timber harvesting base, also referred to sometimes as a forest set-aside. Avoided deforestation refers to keeping land in forest that would otherwise be converted to another use. Once deforestation is avoided, the forest can either be preserved (no timber harvesting allowed) or maintained as a timber-producing forest with harvests allowed.

smaller, region-specific mitigation incentives, in contrast to the national-level payment scenarios evaluated here. Their leakage estimates are derived by simulating a specific level of mitigation in a given region for a single activity and then comparing model results for that selected activity level to the United States as a whole. They assess forest set-asides or preservation of lands likely to remain in forest (100,000 acres of old growth in the PNW and 600,000 acres in the South), avoided deforestation on lands with potential for conversion to agriculture, and afforestation (a 10-million-acre level in each region). These two studies taken together can provide some sense of the range of forest carbon leakage estimates in the United States by activity and region.

The national afforestation estimate in Table 6-2 (24 percent) falls in the 18 to 43 percent range found for regional leakage in U.S. afforestation by Murray et al. (see Table 6-3). But in contrast to this study, where afforestation generates the largest leakage of any of the activity scenarios evaluated, Murray et al. find in some cases larger leakage estimates for the other forest-sector activities: forest preservation and avoided deforestation (Table 6-4).

Table 6-3: Afforestation Regional Leakage Estimates from Murray et al. (2004)

Region	Leakage %
Northeast	23.3
Lake States	18.3
Corn Belt	30.2
Southeast	40.6
South-Central	42.5

Forest preservation leakage was found to vary from 16 percent in one region (PNWW) to almost 70 percent in another (South-Central). Forest preservation can generate relatively high leakage if it simply shifts harvests to another location, which is what the results for the South-Central region suggest. There is less leakage from preservation in the PNWW, in part, because the harvests are shifted to other regions where the losses in carbon would not be as high as they are in the carbon-rich forests of the Pacific Northwest.

Leakage for avoided deforestation is found to vary from slightly positive leakage (i.e., net positive GHG effects off-site) in the Corn Belt, to about 8

Table 6-4: Forest Preservation and Avoided Deforestation Regional Leakage Results from Murray et al. (2004)

Region	Leakage %	
Forest Preservation (Set-aside)		
Pacific Northwest-Westside (PNWW)	16.2	
South-Central (SC)	68.8	
	Leakage % Harvesting Allowed on Preserved Forests?	
Region	**No**	**Yes**
Avoided Deforestation		
Pacific NW-East Side (PNWE)	8.9	7.9
Northeast (NE)	43.1	41.4
Lake States (LS)	92.2	73.4
Corn Belt (CB)	31.5	–4.4
South-Central (SC)	28.8	21.3

percent for the PNWE, to leakage topping 40 percent in the Northeast and Lake States, where it reaches 73 to 92 percent. Leakage is higher when no harvesting is allowed on the lands saved from deforestation, as harvests are shifted to other forests as described above.

Other studies in the literature do not address GHG leakage directly but focus on the market activity-shifting that underlies GHG leakage. For instance, Wear and Murray (2004) used an econometric model of the U.S. softwood lumber market to simulate the effect of reducing timber sales in the Pacific Northwest. Federal restrictions on the harvest of old-growth timber in the 1990s resulted in an 85 percent reduction in harvest volume on public lands. Wear and Murray found that 43 percent of timber harvest reductions in the West region alone leaked away into other harvests within the region, that 58 percent leakage occurred when the continental United States was considered, and that fully 84 percent of the leakage occurred when the United States and Canada were included in the analysis.

In the area of agricultural soil management, previous work by Wu (2000) and Wu, Zilberman, and Babcock (2001) examines program "slippage" from CRP adoption in the United States. Slippage refers to the phenomena by which land retirement into the CRP can induce lands outside the program to enter into cultivation and offset the direct benefits of land retirement. These studies find that 10 to 20 percent of direct CRP benefits are offset by slippage. The agricultural soil carbon sequestration leakage estimate in this study (5.7 percent) is slightly below, but in the same ballpark as, those slippage estimates.

Leakage Summary

Several key findings emerge on leakage from both this study and the extant literature.

First, *afforestation, forest preservation, and avoided deforestation, if targeted individually, could have significant to very large leakage*—depending on the region and how incentives for mitigation are provided. The forest economy involves multiple feedbacks between markets for land, other inputs, and timber. So when GHG incentives are confined to just one part of the forest production system—land use, management, harvest timing—it is more than likely that another part of the system will be affected, often in ways that diminish the net GHG mitigation for the entire forest system. For instance, when afforestation is awarded GHG price incentives and forest management is not, then forest management intensity and carbon tend to decline. Likewise, when harvests are restricted in certain areas but allowed to vary freely elsewhere, the market will tend to shift the harvests and cause leakage.

Second, this key finding follows directly from the first, namely, *leakage appears minimal if all forest carbon activities are included for payment together.* For instance, if afforestation and forest management are targeted together, very little leakage occurs because leakage from afforestation occurs through carbon reductions from reduced forest management. Forest management is reduced because of the corresponding decline in timber prices and incentive to invest in forest management. When incentives are provided to forest management, "good" leakage may occur as the sectors reallocate land and management in response to the forest-sector incentives, and the reallocation of resources in agriculture leads to a slight decline in agricultural emissions.

Third, *leakage from individual activities outside the forest sector appears to be small.* The results in this study suggest that leakage from payments targeting biofuels and agricultural activities is quite small, roughly 0 to 5 percent. Therefore, any accounting adjustments for leakage could fall more heavily on forest-sector activities than on agriculture.

Fourth, *leakage varies by region for a given mitigation activity, reflecting differing levels of market response for wood products or other commodities within and across regions.*

Fifth, *leakage rates vary over time because of forest carbon dynamics; therefore, leakage estimates may* *vary depending on the time frame of analysis.* FASOMGHG results here show that most leakage due to targeted afforestation occurs within the first 2 decades.

Finally, while only early analyses are available to date, it appears that *the broader the spatial scale in which market leakage is evaluated for an activity that produces commodities traded in that market, the higher the leakage estimated*. The FASOMGHG model does not capture leakage due to GHG incentive responses outside the United States. However, the FASOMGHG results in this study show that, at least for afforestation, leakage may be relatively confined to within the regions directly affected by incentives for mitigation. For harvest restrictions, the spatial scale is wider, because the results of Wear and Murray (2004) clearly show higher leakage rates as the number of regions in the North American timber market included in the analysis increased. Therefore, a more global view is needed to better assess mitigation activities and incentive approaches that might cause shifts in production to other regions of the world.

Other Project Implementation Considerations

A number of other implementation issues should be considered when evaluating project-based or other selected activity approaches to GHG mitigation in the forest and agriculture sectors. These implementation issues are reviewed below and are not explicitly reflected in the FASOMGHG scenarios throughout this report.

Measurement, Monitoring, and Verification (MMV)

MMV is the process by which the amount of GHG mitigated by a project is measured, the measurements are monitored over time to ensure that all relevant GHG flows are accounted for, and the monitored measurements are verified to demonstrate to external parties that the emission reductions and/or sequestration have occurred. For carbon sequestration projects, this process can involve a range of methods, including repeated measurement of sample plots using refined scientific procedures, collection and analysis of aerial photographic and satellite image data, and use of ecosystem process models to simulate likely outcomes when observation is difficult.

The ability to measure GHG effects in forestry and agriculture depends a great deal on the

- GHG of interest,
- number and location of affected carbon storage pools,
- way in which the GHGs are exchanged between ecosystems and the atmosphere,
- precision that is acceptable for reporting and verification purposes, and
- cost one is willing to pay to develop the measurements.

For instance, the amount of carbon stored above ground in trees is relatively easy to measure, but the amount of carbon stored in soils is more difficult. Detecting the change in soil carbon can generally be more difficult because of a high degree of spatial variability and the fact that any change may be small relative to the size of the existing soil carbon stock. See the following for more detail on MMV issues for forestry and agricultural sequestration projects: Chapter 5 (e.g., Table 5-7) in IPCC (2000); CASMGS (2003) Carbon Measurement and Monitoring Forum at www.oznet.ksu.edu/ctec/ Fall_Forum.htm; and Brown (2002).

CH_4 emissions from livestock enteric fermentation are difficult to measure at the herd level, but monitoring CH_4 emissions avoided through manure management systems that use the CH_4 for energy production is relatively easy, because the CH_4 is directly tied to the amount of kWh produced. Likewise, CO_2 emissions reduction from replacing fossil fuels with biofuels is a relatively straightforward measurement because of its correspondence to actual, observable market transactions. In light of these factors, MMV requirements need to be taken into consideration before embarking on a project, because this can affect the ability to demonstrate credible mitigation effects and can substantially affect the cost of the project.

Market Assembly and Brokering of Mitigation Activities

For a GHG mitigation market to work, buyers and sellers must be brought together to consummate transactions. Some process is necessary by which GHG mitigation benefits are assembled and brokered. Without this, the economic incentives for mitigation may not flow to those who can supply the mitigation at a cost that is less than or equal to the price that a buyer is willing to pay. When there are few numbers of buyers and sellers (i.e., the market is thin), this may create an inefficient process of search and discovery. When there are more market participants, a role for third parties to broker and assemble transactions could evolve. Consequently, the development of this market-making infrastructure may need to be considered in any market-based GHG mitigation program.

Even in the case of government-sponsored landowner incentive programs, rather than a private market for mitigation, some infrastructure is necessary for delivering the incentive to the landowner. In the United States, there is a long history of these programs being delivered to farmers, ranchers, and forestland owners through a variety of outreach mechanisms such as agricultural and forestry extension programs at federal and state agencies and universities.

Transaction Costs

The various implementation issues just discussed (e.g., contracting, risk management procedures, MMV, market assembly) all impose what can be termed collectively as transaction costs on developing and operating a GHG mitigation project. The liability for these transaction costs may fall on the buyer, the seller, or both parties.

If the seller is liable, this adds to their costs and increases the amount they need to be compensated to voluntarily engage in the transaction. If the buyer is liable, this lowers the amount they are willing to pay for a unit of mitigation, because the full cost of the unit includes the transaction cost. But regardless of who bears the direct liability, the cost and risk of undertaking these activities directly affect the value of the transaction itself.

Many of these transaction costs operate under scale economies; that is, because they involve many costs that are largely fixed, the cost per transaction declines with the number of transactions covered (Mooney et al. 2004b). For example, a reversal risk management plan and MMV plan will not likely be 10 times larger for a project generating 100,000 t CO_2 Eq. per year of mitigation than one that generates 10,000 t CO_2 Eq. per year. In addition, GHG contracts may need to be bundled or aggregated to a minimum lot size for market exchange. For instance, the Chicago Climate Exchange, a voluntary system for GHG trading, requires a minimum trading block of 12,500 t CO_2 Eq. If conservation tillage practices generate 0.5 t CO_2 Eq., per acre per year, this will require bundling across 25,000 acres. Therefore, large operations will be able to bundle more cost-effectively than small ones. Finally, market assembly or brokering costs are likely to be much lower on a per-unit basis for a large volume market than for a small volume market. Note that the absolute size of the transaction costs per unit does not matter as much as the ratio of that cost to the per-unit value of the transaction.

Evidence on the size of transaction costs associated with forest and agricultural practices is quite limited. Relatively few GHG mitigation projects in forestry and very few in agriculture have been implemented in the field. Certain components, such as the cost of MMV, have been recorded in some cases and have been relatively low for projects operating on a fairly large scale. Kadyszewski (2001) estimates costs of less than \$0.25/t C Eq. (\$0.07/t CO_2 Eq.) for forest carbon measurement. Mooney et al. (2004a) estimate the measurement and monitoring costs of soil carbon benefits from the adoption of more intensive cropping practices in Montana as generally less than \$1/t C Eq. (\$0.30 per t CO_2 Eq.). However, costs will depend primarily on the degree of precision required, heterogeneity of the landscape, frequency of sampling, and project size (Mooney et al. 2004a; Brown, Masera, and Sathaye 2000).

While measurement costs may be low, on the other hand anecdotal evidence suggests that some transaction cost components could be considerable. For instance, if trading tends to be conducted in large units (e.g., 100,000 t CO_2 blocks), given the sequestration rates per unit of output for many of the activities in forestry and agriculture, each transaction could require aggregating hundreds or thousands of landowners. These costs are likely to be considerable. Alston and Hurd (1990) found that the costs of delivering government programs to farmers in the United States are on the order of 25 to 50 percent of the value of the program payments.

The FASOMGHG model simulations throughout this report do not include transaction costs. This is not problematic if transaction costs are low, because their omission from the analysis would then be trivial. If transaction costs are uniform across options, then one can adjust the GHG price incentives accordingly and roughly determine the mitigation potential. On the other hand, if per-unit transaction costs differ among afforestation, forest management, agricultural soil carbon sequestration, and biofuels, then the portfolio of options selected at each GHG price will change. Consistent data on the size and distribution of transaction costs across mitigation options would be a helpful addition to analyses such as those presented in this report.

Preliminary Assessment of Implementation Factors by Major Mitigation Activity

The discussion above suggests that major mitigation activities have different characteristics with regard to project-based implementation. Tables 6-5 and 6-6 evaluate mitigation options across the various implementation issues, quantitatively where FASOMGHG results are available, and qualitatively otherwise. A rigorous comparison of activities along each of the implementation factors requires additional analysis and is beyond the scope of this study. A review of Tables 6-5 and 6-6 suggests the following:

- Afforestation has significant leakage varying by regional market conditions, but MMV and establishment of a baseline may be relatively straightforward because land-use change can be observed. Additionality is likely to be high. Reversal risk is relatively high without constraints imposed.
- Forest management, which is an economic option at a wide range of options, has some project implementation challenges. MMV and baseline setting may be more challenging than afforestation, for example, because changes in management practices rather than readily observable changes in land use are involved. Setting a baseline and determining additionality may be more difficult.
- Agricultural soil carbon sequestration appears to have low leakage but may require significant site-specific data to determine a baseline and additionality and monitor project activities. Risk of reversal from increased tillage is moderate to high and may require site-specific data to assess.
- Agricultural CH_4 and N_2O mitigation options and biofuels appear to have low leakage and may have a low likelihood of reversal. Some options (e.g., CH_4 capture from manure management and biofuels) in general appear to be readily monitorable and likely to be additional, while others (e.g., soil N_2O mitigation options) may be more challenging to evaluate for these issues.
- Biofuel offsets, though a relatively high-cost option in the economic analyses above, have a number of implementation advantages in that they are relatively easy to measure, monitor, and verify; highly additional under current energy market conditions; and have low reversal risk.

Taken together, it is interesting to observe that some of the lower cost mitigation options found in the economic analyses (e.g., forest management and agricultural soil carbon sequestration) may have implementation challenges, in contrast to options such as biofuels implementation and afforestation, which have higher opportunity costs (in the economic analysis) but possibly lower implementation transaction costs.

Table 6-5: Implementation Issues for Selected Activities and Projects: Leakage Estimates from FASOMGHG and MMV

Activity	Leakage Potential (and Estimates)	MMV Difficulty
Afforestation	Moderate U.S. average: 28% Regions: 18-42%[a]	Relatively easy to measure, monitor, and verify forest establishment. Measuring carbon is relatively straightforward for above-ground carbon, less so for below-ground carbon. Models can be used instead of direct measurement if program allows.
Forest management	Likely some leakage through reduced afforestation No separate estimates available	Moderate to difficult to measure, monitor, and verify specific management actions attributable to a project. Measuring carbon in established stands is not exceedingly difficult, but tying the change in carbon to specific practices may be.
Agricultural soil carbon sequestration	Low 6%	Easy-moderate to measure, monitor, and verify across adopting practices. Moderate–difficult to directly estimate carbon consequences across the landscape. Models can be used instead of direct measurement if program allows.
Agricultural CH_4 and N_2O mitigation	Low NA	Easy (e.g., for manure management CH_4 tied to electricity-generating systems), difficult for dispersed emissions (e.g., enteric fermentation at the herd level).
Biofuel offsets	Low <1%	Easily tied to the biofuel market transactions.

[a] Results from five regions in Murray et al. (2004) reported above.

Per-Acre Payments for Carbon Sequestration to Address Measurement Difficulties

GHG mitigation activity could be designed to economize on transaction costs, particularly MMV costs. The incentive approaches evaluated thus far have paid for GHG mitigation on a dollar-per-tonne basis. An alternative is for payments to be based on a per-unit area (acre) tied to the adoption of a specific mitigation practice. This approach is similar to a number of land-based conservation programs in the United States, such as the CRP and The Environmental Quality Incentives Program (EQIP). This approach may economize on transaction costs because it relies on simple verification that the land-use change has occurred on the land in question, rather than quantification of the GHG tonnes that have been mitigated. The per-acre versus per-tonne issue is commonly referred to as "practice versus performance payments."

Scenario Description

Two of the carbon sequestration options considered thus far—afforestation and agricultural soil carbon sequestration (tillage change)—are evaluated because they represent the dominant mitigation activities at medium-high and low GHG prices, respectively, and they are distinct activities that can be tracked relatively easily at the per-acre level. Other activities may be more difficult to pay for on a per-acre basis, because they are not space extensive (e.g., CH_4 and N_2O mitigation activities assessed in Chapter 4).

Per-acre results are evaluated against the targeted \$15/tonne CO_2 payment scenario presented in Chapter 5 (i.e., the situation under which the selected activity—and only the selected activity—

receives payments at a rate of $15 per tonne). In the per-acre payment case, the activity and only the activity will receive payments of $100 and $15 per *acre* per year for the entire 10-decade simulation period for afforestation and tillage change activities, respectively. These per-acre values were selected because they roughly reflect the equivalent per-unit area payments of $15/tonne for representative sequestration rates for the two activities (about 6 to 7 t CO_2 per year for afforestation and 1 t CO_2 per year for tillage change).[3]

Two types of per-acre payment approaches are evaluated for each activity:

- **Uniform**—any and all acres within the United States that adopt the practice receive the same

Table 6-6: Qualitative Consideration of Implementation Issues for Selected Activities and Projects: Baselines, Additionality, and Reversal Risk

Activity	Baseline Setting Feasibility	Potential for Additionality	Reversal Risk of GHG Benefits (Permanence)
Afforestation	Credible baseline at adequate spatial and temporal resolution is likely. Involves observable land-use change.	High in most places within United States, unless locally high tree-planting rates.	Moderate if timber or land prices change or natural disturbances (fire, pests).
Forest management	Difficult to observe practices with remotely sensed data. Includes many practices varying by forest type, etc.	Likely need to demonstrate introduction of alternative practices.	Moderate if timber or land prices change or natural disturbances (fire, pests).
Protection (avoided deforestation)	Likely to require baseline deforestation rates by forest type and region, projected into future. Involves observable land-use change.	Likely high if new protection status is conveyed or high deforestation rates; low, if not.	Low if legal protection and it is enforced. High if susceptible to wildfire, has uncertain legal status, major commodity price changes, etc.
Agricultural soil carbon sequestration	Need data on continuous tillage practices and rates of alternative tillage adoption.	High if conventional tillage persists into future; low otherwise.	Moderate–high: potential seasonal tillage change (weed control); or change in crops or tillage practices in response to commodity prices or programs.
Agricultural CH_4 and N_2O mitigation	Remote sensing not useful. Need activity data per unit of production. If adequate data, likely credible baseline.	Moderate–high.	Low. No carbon storage subject to re-release involved.
Biofuel offsets	Similar to afforestation and soil tillage options but may require energy sector data to determine baseline demands for biofuels.	High based on recent market trends.	Low. Primary benefit does not involve carbon storage subject to re-release, although response to changing commodity prices could affect soil carbon.

[3] Note that the per-acre payment values were based on average carbon yields per acre nationwide but, as shown below, the realized gains per acre will be lower than average because of the inefficient nature of the incentive payments that either do not differentiate or differentiate imperfectly by carbon yield per acre.

per-acre payment for changing practices ($100 for afforestation and $15 for tillage change).

- **Productivity based**—any given acre receives one of five payment levels for each activity. The payments are based on the relative carbon productivity of the acre.[4]

By at least partly basing payments on carbon productivity, the productivity-based per-acre payments should operate more closely to per-tonne payments than uniform payments do. The productivity-based approach more closely follows programs such as the CRP, which have graduated payments for changes in land use and practices based on site characteristics. In contrast, the uniform payments should induce more inefficiency. The results below bear this out.

Per-Acre Payments for Carbon Sequestered through Afforestation

Results of the per-acre payments for afforestation are presented in Table 6-7 and compared to the $15 per-tonne afforestation-only payment scenarios from Chapter 5. The uniform $100 per-acre payment approach is substantially less efficient than the per-tonne approach. On an annualized basis over the projection period, the uniform per-acre payments generated only about 30 percent as much sequestration as payments on a per-tonne basis (41.9 vs. 137.4 Tg CO_2 Eq.). However, the value of the payments is about 60 percent as much ($790 MM vs. $1.36 billion). For the year 2015, which is the midpoint of the first decade of the simulation, only about one-quarter the amount of carbon is sequestered even though one-half as much acreage is afforested. This demonstrates a critical shortcoming of uniform per-acre payments, namely, that the payments are made without regard to the biophysical sequestration potential of the site—each afforested acre receives the same payment. Therefore, tonnes sequestered on a low productivity site are more costly than tonnes sequestered on a high productivity site, which is an economically inefficient way to sequester a given amount of carbon.

Table 6-7 shows how modifying the payments based on site productivity can improve the effectiveness of the per-acre payment approach. Productivity-based payments generate about 70 percent more carbon (annualized) than the uniform payments, although the cost of the payments rises by only about one-third. In the first decade (proxied by the 2015 results), the amount of carbon sequestered matches that in the dollar-per-tonne payment scenario. However, when compared

Table 6-7: Per-Acre vs. Per-Tonne Payment Approaches for Afforestation: 2015 and 2010–2110 Annualized

	Payment Scenario		
	$15/t CO_2 Eq.	$100/Acre Uniform	$100/Acre Productivity Based
Year 2015			
GHG mitigated (Tg CO_2 Eq. per year)	88.8	23.5	89.9
Net afforestation (MM acres)	10.1	5.1	11.3
Over 2010–2110 projection period (annualized)			
GHG mitigated through afforestation (Tg CO_2 Eq. per year)	137.4	41.9	68.6
Value of GHG payments (billion $ per year)	$1.36	$0.79	$1.06

[4] Candidate acres are ordered by carbon productivity and divided into quintiles. The middle quintile received the default value payment ($15/acre for tillage change or $100/acre for afforestation), the top two quintiles received higher per-acre payments, and the lowest two quintiles received lower per-acre payments. Payments were based on relative carbon productivity, yielding a payment range of $5 to $16 per acre for tillage change and $65 to $130 per acre for afforestation.

to the per-tonne results over the entire projection period, the productivity-based payment approach—although superior to the uniform payment approach—is still less efficient than the per-tonne approach in that it generates only half as much carbon on an annualized basis at a cost that is only about 22 percent lower. A payment approach that has more than the five differentiated payments employed here, however, would operate even more closely to the per-tonne approach.

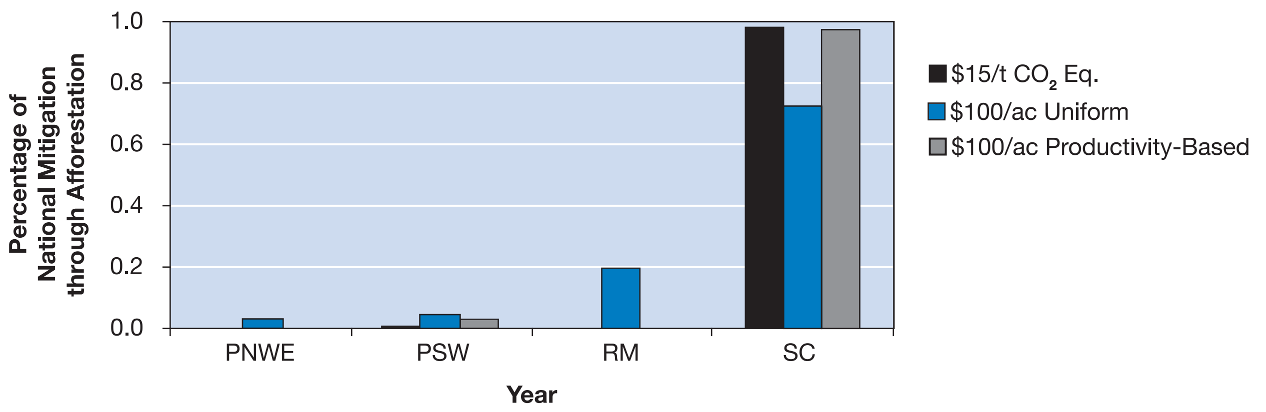
Changing the nature of the payments also changes the regional distribution of afforestation responses (see Figure 6-2). Under all payment approaches, the South-Central region has the largest afforestation response (over 70 percent of the national total); however, the uniform payment approach shifts some of the South-Central's afforestation carbon share to other regions, notably the Rocky Mountains. Again, this reflects the change in emphasis from paying for the highest carbon-yielding afforestation to paying for any afforestation at the same amount. The Rocky Mountains region's biophysical sequestration yield is less than the South-Central region's but receives the same payment and therefore comprises a larger share of the program under uniform payments than under per-tonne or distributed payments.

Per-Acre Payments for Agricultural Soil Carbon Sequestered through Changes in Tillage

Similar patterns emerge when comparing the per-tonne and per-acre payment approaches for agricultural soil carbon sequestration (see Table 6-8). As with afforestation, the uniform per-acre payment approach is substantially less efficient than the per-tonne or productivity-based payment approach. The uniform payments cost more than half as much as the per-tonne payments but yield only about one-fifth as much carbon. This result is similar to the findings of Antle et al. (2003), who find that per-acre contracts for soil carbon sequestration are up to five times as expensive as per-tonne contracts. As with afforestation, the inefficiency situation is partly remedied with the introduction of productivity-based payments, which generate more than half the amount of carbon at about 85 percent of the cost of the per-tonne approach.

The main factor underlying the inefficiency of uniform payments is found by looking at the distribution of tillage practices in the first decade (2015). The primary response under uniform payments is the adoption of conservation tillage, rather than the more substantial zero tillage practice. Farmers are paid the same for either practice and therefore adopt the less costly conservation tillage, even though it does not sequester as much carbon.

Figure 6 2: Regional Shares of Afforestation Carbon Sequestration by Payment Approach
Shares based on annualized mitigation, 2010 2100.

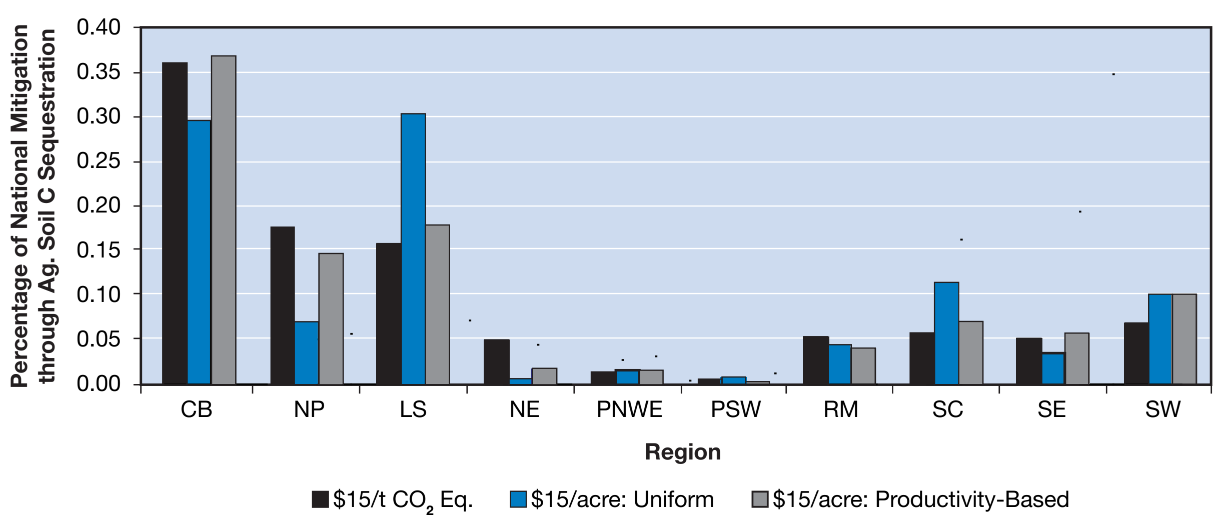


The regional distribution of agricultural soil carbon sequestration is also moderately affected by the payment approach (see Figure 6-3). Moving from per-tonne to a uniform per-acre payment, the regional shares shift some from the Corn Belt and Northern Plains to the Lake States and South-Central regions. Switching to productivity-based per-acre payments would restore the regional shares to a pattern roughly the same as the per-tonne payments.

Table 6-8: Agricultural Soil Carbon Sequestration Payment Approaches: 2015 and 2010–2110 Annualized

	Payment Scenario		
	$15/t CO_2 Eq.	$100/Acre Uniform	$100/Acre Productivity-Based
Year 2015			
GHG mitigated (Tg CO_2 per year)	190.9	41.9	127.7
Conservation tillage (MM acres)	2.9	119.5	0.2
Zero tillage (MM acres)	169.4	60.1	192.1
Over 2010–2110 projection period			
GHG mitigated through tillage change (Tg CO_2, annualized)	154.2	33.7	81.7
Value of GHG payments (billion $, annualized)	$1.61	$0.90	$1.36
Mitigation delivery efficiency			

Figure 6 3: Regional Shares of Agricultural Soil Carbon Sequestration by Payment Approach



CHAPTER 7

Non-GHG Environmental Co-effects of Mitigation

Chapter 7 Summary

Changes in land-use and management practices as a result of GHG mitigation actions can produce non-GHG environmental co-effects. Wide-scale conversion of agricultural land to forest may affect water quality, air quality, soil quality, and biodiversity. FASOMGHG predicts a net increase in forestland of 5 million acres at the $15/t CO_2 Eq. (or $55/t C Eq.) price and 58 million acres at the $50/t CO_2 Eq. (or $183/t C Eq.) price by the year 2055. All nonpoint source pollutant loadings to national waterways modeled in FASOMGHG, except pesticides, are predicted to decline from the baseline amounts under all GHG prices. Pesticides increase slightly under the low GHG prices but decline under the higher prices. Even at low GHG prices, these reductions in nonpoint source pollutant loadings may improve national and regional water quality, though effects would likely vary substantially across regions. Co-effects of GHG mitigation on biodiversity (not modeled in this analysis) may be both positive and negative. The net impact will depend on the baseline land cover and type of cover to which it is converted in response to GHG incentives.

This report mainly focuses on quantifying and evaluating the mitigation potential for net GHG emission reductions through forestry and agricultural activities. However, the large-scale changes in land use and land management practices projected in a number of the mitigation scenarios could have a substantial impact on resource flows in other (non-GHG) aspects of environmental quality. GHG mitigation co-effects in the forest and agriculture sectors include changes in water quality, air quality, soil quality, biodiversity, and aesthetics (McCarthy et al. 2001). Therefore, assessing the net societal effects of GHG mitigation will depend on more inclusive analysis that captures a range of expected effects within and across different impact categories (Elbakidze and McCarl 2004).

This chapter broadens the scope of the assessment by examining some key ancillary land-use and environmental effects that result from the forestry and agricultural activities and analytical scenarios described earlier. This report focuses on GHG effects as the primary objective, so the non-GHG environmental effects are reported here as ancillary. Conversely, many existing land-based programs are designed to attain non-GHG environmental objectives (e.g., erosion control, reduced nonpoint agricultural runoff, habitat preservation) but also may have GHG consequences. In that regard, GHG flows could be viewed as a co-effect of those programs. While assessing the general environmental effects of existing or proposed land management programs and their concomittant GHG benefits would be a way to estimate the latter, this approach remains outside the scope of this analysis.

Land Use

One of the key changes projected by the FASOMGHG model in most of the GHG mitigation scenarios is large-scale adjustments in land use and land management. As noted in Chapter 4, land tends to convert from agriculture to forests and biofuels in response to GHG price incentives, particularly under higher GHG prices. Underlying this general trend are numerous adjustments across the major land uses, namely cropland, timberland, pastureland, and land devoted to biofuels. For instance, at higher GHG prices, biofuels play an important role in GHG mitigation, and biofuel production uses substantial land area.

To get a sense for the overall adjustments projected by FASOMGHG, land uses are compared for the baseline, $15, and $50 constant GHG price scenarios for 2015 and 2055. (The $50 price is used here to evaluate the effect of higher prices on stimulating biofuel penetration, which is minimal at lower prices.) Under the baseline, crop and timberland use declines, while pastureland use increases. For the two GHG price scenarios, land use initially shifts heavily toward forests in 2015, as expected. For the $15 per tonne CO_2 scenario, timberland area increases 19 million acres, and for the $50 per tonne scenario, timberland area increases by 97 million acres by 2015. By 2055, however, much of this additional forest has converted out of timberland into other uses. Net timberland gain in 2055 for the $15 per tonne scenario is only about 5 million acres, and for the $50 per tonne scenario, it is around 58 million acres.

The results in Chapter 4 show that, as GHG prices rise, biofuels become a more important part of the future GHG mitigation portfolio. Table 7-1 illustrates the implications of that adjustment for land use. Large areas of land, 42 million acres, are ultimately devoted to biofuel production in the $50 per tonne CO_2 Eq. GHG price scenarios by 2055. Thus, although cropland and pastureland both decline relative to the baseline, this land converts to biofuel and forest uses.

Regional Distribution of Land Uses

Land-use changes projected to occur in response to GHG price scenarios are not evenly distributed. Figures 7-1 and 7-2 show the proportion of land in each region devoted to different land uses in 2015 and 2055 under the baseline scenario and the $15 and $50 constant GHG price scenarios. Three interesting trends emerge.

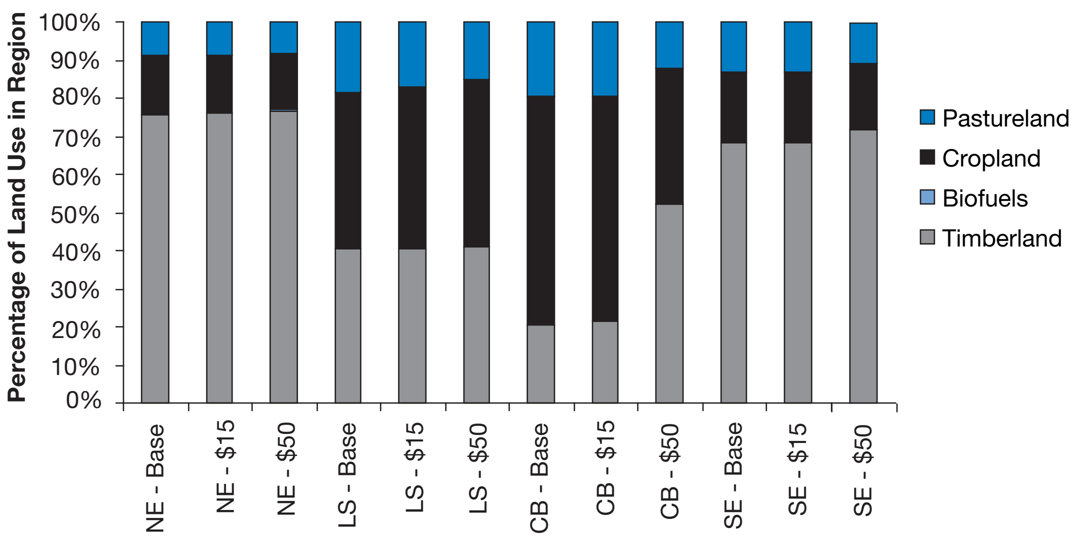
Table 7-1: Land Use under the Baseline, $15, and $50 (Constant) GHG Price Scenarios: 2015 and 2055
Quantities are in million acres.

	GHG Price Scenario ($/t CO_2 Eq.)		
Land Use	**Baseline**	**$15**	**$50**
2015			
Cropland	332	325	296
Pastureland	384	381	370
Timberland	333	352	430
Biofuels	0	0	1.4
2055			
Cropland	241	229	161
Pastureland	448	444	409
Timberland	303	308	361
Biofuels	0	4.5	42

Note: Land areas do not sum to the same value in each year because some uses are not included.

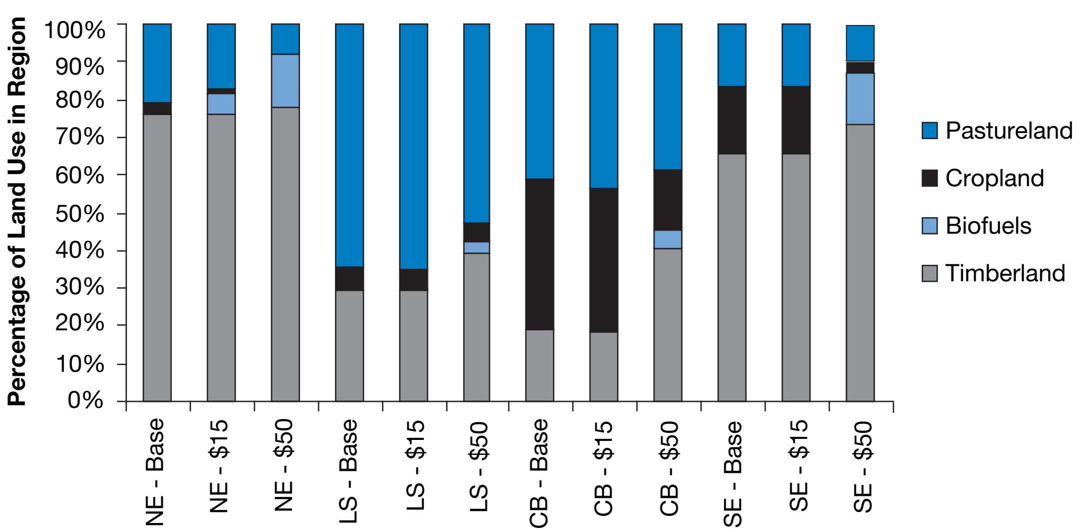
First, the proportion of land devoted to timber increases in the eastern United States with GHG prices. For higher GHG prices, the expansion of timberland is substantial in regions with less timberland initially, such as the Corn Belt. By comparison, in the western United States, the timberland proportion expands only slightly relative to the baseline. Most of this expansion

Figure 7 1a: Land Use Allocation by Eastern U.S. Regions in 2015: Baseline and the $15 and $50 Constant GHG Price Scenarios



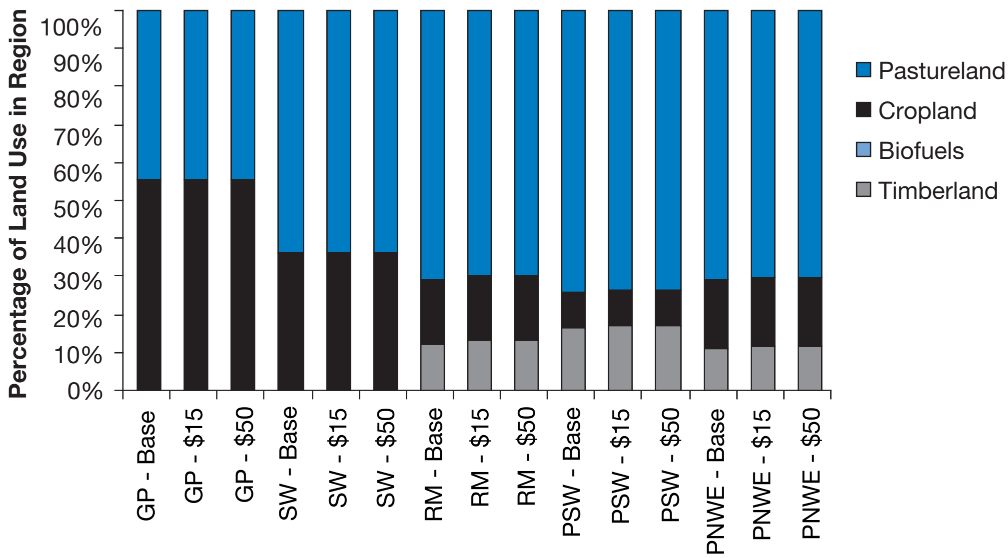
Notes: NE = Northeast; LS = Lake States; CB = Corn Belt; SE = Southeast

Figure 7 1b: Land Use Allocation by Eastern U.S. Regions in 2055: Baseline and the $15 and $50 Constant GHG Price Scenarios



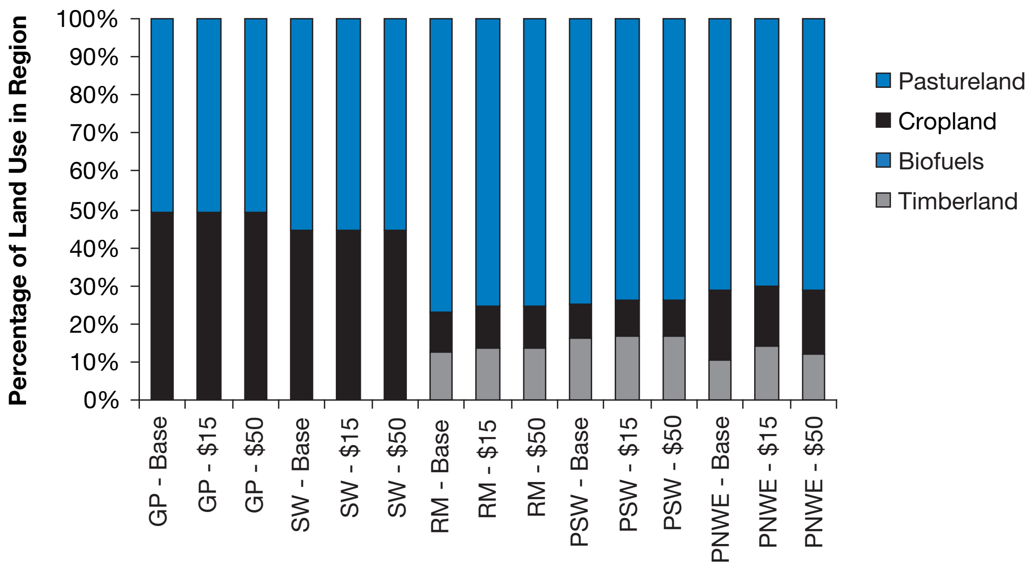
Notes: NE = Northeast; LS = Lake States; CB = Corn Belt; SE = Southeast occurs at the $15 GHG price, while for the larger $50 GHG price, there is little additional timberland expansion compared to the $15 GHG price scenario. These results generally make sense in that regions that already have substantial forest area (e.g., the Northeast) or regions that have few productive sites remaining for forests (i.e., many western regions) cannot substantially

Figure 7 2a: Land Use Allocation by Western U.S. Regions in 2015: Baseline and the $15 and $50 Constant GHG Price Scenarios



Notes: GP = Great Plains; SW = Southwest; RM = Rocky Mountains; PSW = Pacific Southwest; PNWE = Pacific Northwest, East Side of Cascades (Pacific Northwest West Side of Cascades is not shown due to a lack of data.)

Figure 7 2b: Land Use Allocation by Western U.S. Regions in 2055: Baseline and the $15 and $50 Constant GHG Price Scenarios



Notes: GP = Great Plains; SW = Southwest; RM = Rocky Mountains; PSW = Pacific Southwest; PNWE = Pacific Northwest, East Side of Cascades (Pacific Northwest West Side of Cascades is not shown due to a lack of data.)

increase timberland area with low or high GHG prices.

Second, cropland area declines in all regions over time under both GHG price scenarios, except in the Southwest (SW). There are fewer alternative uses for cropland in the Southwest region (i.e., fewer opportunities to plant trees and/or biomass crops) where more cropland is irrigated. Irrigation also makes less sense for alternatives such as biofuels or timber production.

Third, biofuels become a more important component of mitigation as GHG prices rise. Under the \$15/t CO_2 Eq. constant GHG price scenario, only land in the Northeast is devoted to biofuels. Under a GHG price of \$50 per tonne, however, over 40 million acres could be devoted to production of biofuels nationally by 2055. Regionally, all of this biofuel production occurs in the eastern United States (Figures 7-1a,b), since U.S. biofuel crops generally are rainfed and require fairly productive sites to be profitable with carbon prices. In most regions, the increases in biofuel production occur on cropland and pastureland, although in the Corn Belt, biofuel production occurs to some extent through conversion of timberland.

Timberland Management Intensity

Substantial changes in the intensity of forest management are underway in the United States, both in the baseline and in the mitigation cases. The forest industry historically focused on methods to extract large, old-growth trees in clear cuts up to the mid-twentieth century. Methods to establish and manage plantations began in earnest in the 1960s, and these efforts continue today.

The success of plantations and recent emphasis on other, noncommercial values of forests has shifted the focus in the last 20 years away from extracting old-growth through large-scale clear-cutting. The industry has shifted toward extracting smaller trees from fast-growing plantations and using alternative, less-intensive methods to extract timber from natural, second-growth stands with minimal forest damage.

The GHG mitigation scenarios explored in this study may influence trends in forest extraction (e.g., the intensification of plantation areas to generate more carbon sequestration). FASOMGHG model results suggest that GHG prices increase timberland management intensity to enhance carbon sequestration, via practices such as additional fertilizers to increase forest growth and thinning operations undertaken to enhance yield. Recent evidence from studies in the southern United States suggests that nitrogen fertilizing, chemical suppression of competition, and other management intensifications can increase biomass on sites from 6 to 20 percent (Siry 2002). With carbon valued for GHG mitigation purposes, the incentives for more intensive management could be heightened.

Agricultural Nonpoint Pollutant Runoff

One of the most important environmental issues facing agriculture in the United States is its contribution, along with forest management and urban development, to nonpoint source water pollution. Nonpoint sources, particularly agriculture, are considered to be the leading source of water quality impairment in U.S. rivers, lakes, and streams (EPA 2000). Siltation, nutrient runoff (such as nitrogen and phosphorous), and pesticides are the primary nonpoint water pollutants from agriculture.

This section of the report focuses on four of the most important runoff components from agriculture: nitrogen, phosphorous, sediments, and pesticides. Individual estimates of inputs or loadings of these pollutants are shown for several GHG price scenarios. For nitrogen and phosphorous, loadings are estimated using algorithms from the EPIC model (Williams et al. 1989) imbedded in FASOMGHG. For soil erosion, the outputs are total soil erosion, based on the Modified Universal Soil Loss Equation (MUSLE). It is not possible here to quantify direct pesticide loadings (field outputs). Therefore, changes in pesticide use are presented to approximate loadings potential.

The substantial changes in land use and management projected under some of the GHG mitigation scenarios in Chapter 4 suggest there could be large potential changes in water quality. First, there is potential to reduce nonpoint source pollution through land-use change, such as shifting land out of agriculture and into forests, and establishing perennial biofuel cover. Both forestry and biofuel production typically use fewer inputs and produce fewer pollutants than traditional crop agriculture. Management inputs (chemical and mechanical) in forestry are applied less frequently and less intensively than in agriculture. There is less experience in and information on pollutants arising from biofuel production. The FASOMGHG model, however, does include nutrient and pesticide requirements as part of the production set for biofuels.

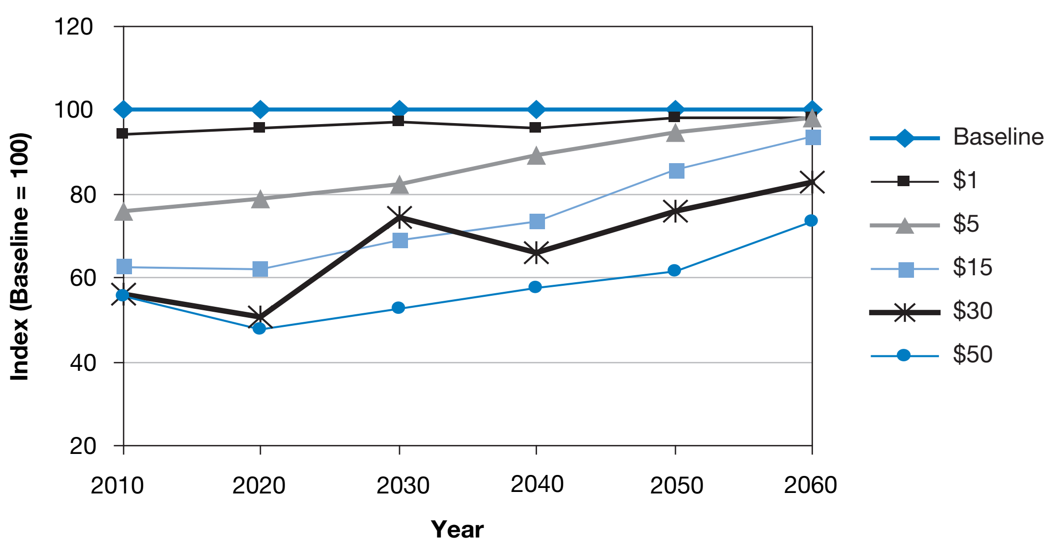
Second, changes in the management of agricultural land could alter the magnitude and quality of farm runoff. Adoption of conservation tillage was originally developed to reduce soil erosion; thus, adoption of conservation tillage to increase soil carbon should reduce sediment lodgings from soil erosion over time. Because phosphorous is typically attached to soil particles, reductions in soil erosion should also reduce phosphorous entering rivers and streams.

The potential effect of conservation tillage on nitrogen and pesticide runoff, however, is less clear. Pesticide use often increases with the adoption of conservation tillage (because of the need for greater weed and other pest control), and conservation tillage reduces yield for certain important crops, such as corn. Consequently, farmers may adjust by adopting more intensive nitrogen and pesticide applications when they adopt conservation tillage. Agricultural soil management practices to mitigate N_2O emissions by reducing fertilizer use also have the joint benefit of reducing nitrogen loadings.

The rest of this section looks more carefully at the estimates provided by FASOMGHG for soil erosion, phosphorous, nitrogen, and pesticides. Each of the variables is evaluated relative to its projected baseline level, normalized to a value of 100 for the purpose of cross-pollutant comparisons over time, and across the range of constant GHG price levels evaluated in Chapter 4.

Adoption of reduced tillage practices induced by the GHG prices reduces soil erosion (Figure 7-3). Soil erosion reductions occur relatively quickly, due mainly to rapid adoption of tillage change and shifts in land from agriculture to

Figure 7 3: Soil Erosion Index over Time by (Constant) GHG Price Scenario (Baseline = 100)



forestry (i.e., over the first 10 to 20 years of the model run). Over time, erosion levels gravitate slightly back toward baseline levels. But these erosion reductions produce annual benefits, implying continuing improvements in water quality over time. Baseline levels of erosion are also declining over time, so that all of the paths shown in Figure 7-3 represent net reductions in erosion relative to today.

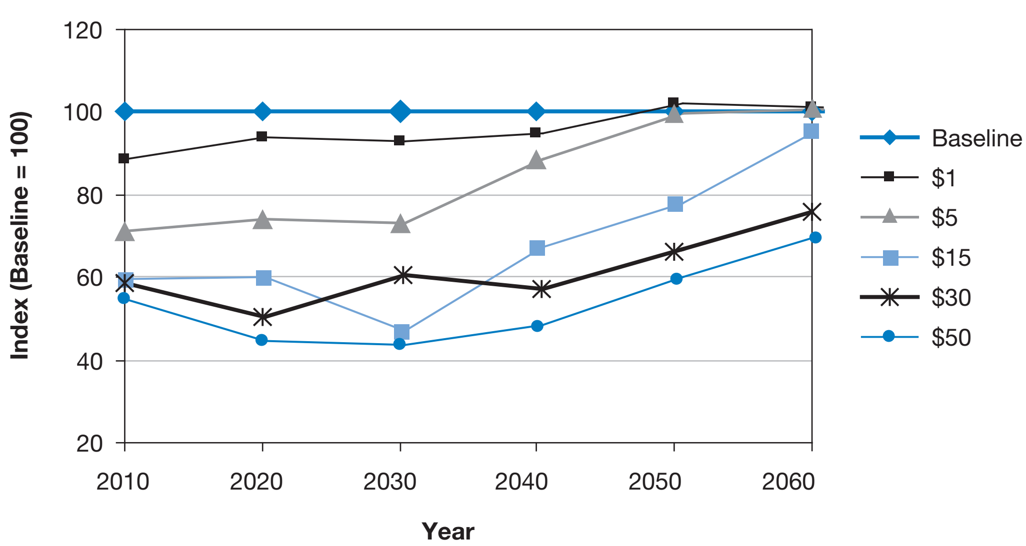
Estimated phosphorous loadings decline with the introduction of GHG prices (Figure 7-4). This decline is roughly proportional to the reductions in erosion, because phosphorous is attached to soil particles. For higher GHG prices in the range of $15 to $50, the reductions in loadings in the initial period are roughly similar, suggesting the maximum reduction in phosphorous may be around 40 percent. In many cases, loadings begin moving back toward baseline levels over time as farmers increase inputs per hectare to make up for yield losses associated with conversion to conservation tillage. Loadings remain lower than baseline levels in total, because overall cropland areas tend to decline with GHG pricing.

Estimated nitrogen loadings decline in all scenarios (Figure 7-5). These reductions, as a percentage of baseline loadings, are smaller proportionally than those for phosphorous and erosion. The initial reduction ranges from 5 to 21 percent under the GHG price scenarios considered. For the lower GHG prices, reductions in nitrogen loadings initially are relatively small, and loadings move back toward baseline levels over time. For the higher GHG prices (>$15 per tonne CO_2), reductions in loadings are larger initially, but, after a while, they begin to rise back toward baseline levels.

The increase in nitrogen applications is in response both to lower crop yields associated with conservation tillage and to higher crop prices. Under the higher price scenarios, farmers in the FASOMGHG model are shown to intensify the use of nitrogen to increase overall production of crops on land that remains in agriculture, and that increase eventually leads to increased loadings over time but still below baseline levels.

Pesticide applications increase relative to the baseline for lower GHG prices (Figure 7-6), as land shifts into conservation and zero-tillage practices. With reduced tillage, farmers often increase pesticide use to control for weeds, pests, and other competition in lieu of mechanical control through conventional tillage practices. These increases result in greater overall pesticide

Figure 7 4: Phosphorous Loading Index over Time by (Constant) GHG Price Scenario (Baseline = 100)



releases under the low-price GHG scenarios. As GHG prices rise, however, more land is converted from agriculture to forestry and biofuels, and aggregate pesticide applications and runoff are projected to decline.

Changes in Agricultural Runoff and Water Quality—Results from a Separate Case Study

Measuring the impacts of these nonpoint source pollution outputs on ambient water quality levels requires additional modeling. The relationship between nutrient or soil runoff and water quality is a complex one, and linking the loading results described above to environmental outcomes is difficult. The actual effects of changes in agricultural runoff on water quality will depend on numerous factors, including existing loads, assimilative capacity, routing of the pollutants through the river and stream network, and nutrient processes in the water (including nutrient limitations), all of which vary substantially from watershed to watershed.

Figure 7 5: Nitrogen Runoff Index over Time by (Constant) GHG Price Scenario (Baseline = 100)

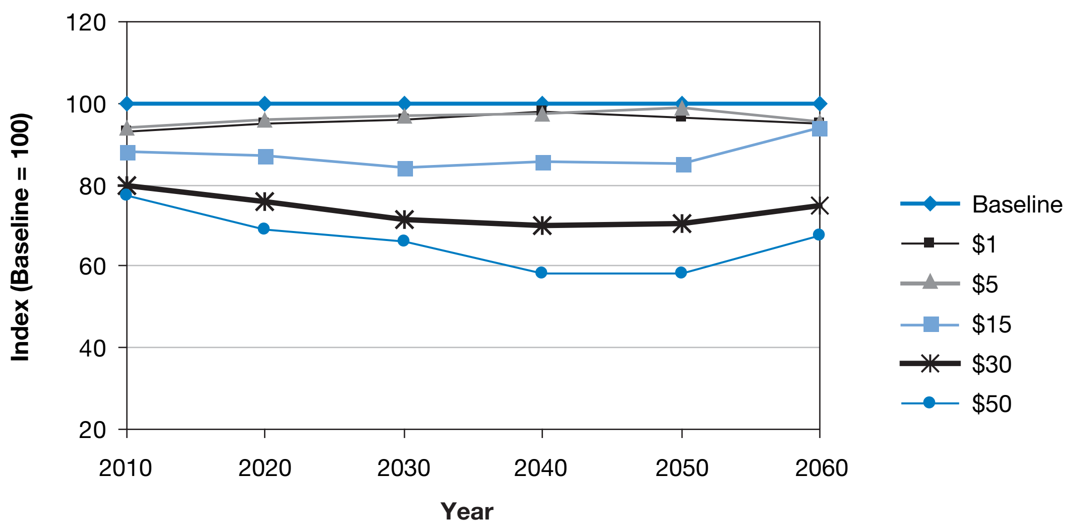
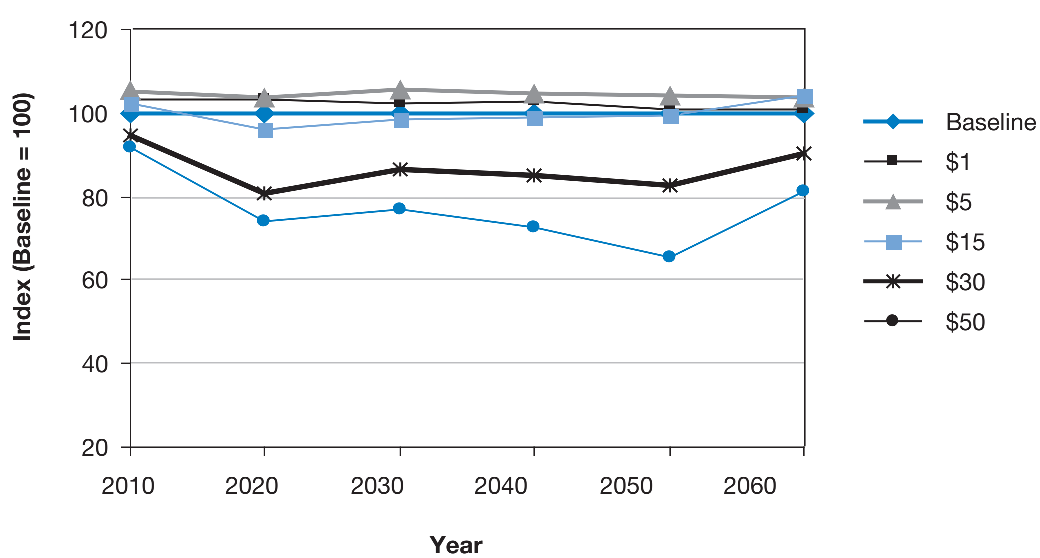


Figure 7 6: Pesticide Index over Time by (Constant) GHG Price Scenario (Baseline = 100)



This section describes a previously conducted case study to show water quality impacts associated with GHG mitigation in agriculture, using a related economic model linked to a water quality model. Note that the case study is from a separate analysis described in Pattanayak et al. (2005) and is not directly a part of the GHG mitigation scenarios performed for this report. However, because the modeling framework and scenarios are so similar between this study and Pattanayak et al., it warrants further discussion here.

The case study linked ASMGHG (McCarl and Schneider 2001), which is in essence the agricultural component of the FASOMGHG model used in this report, with the National Water Pollution Control Assessment Model (NWPCAM), a model developed by RTI International (Research Triangle Institute) for EPA.

NWPCAM was used to estimate regional and national water quality impacts of GHG mitigation scenarios of $6.80 and $13.60 per tonne of CO_2 ($25 and $50/t C, respectively), run through ASMGHG. Similar to scenarios analyzed in this report, GHG mitigation actions taken in ASMGHG include afforestation, agricultural soil carbon sequestration through tillage changes, CH_4 and N_2O reductions through livestock and soil management changes, and biofuel production.

One benefit of the NWPCAM model is that it provides results on water quality outcomes through a water quality index (WQI) that accounts for the loading of different pollutants, as well as the impacts of those pollutants in specific stream segments. The WQI is on a scale from 0 to 100 and was developed for NWPCAM based on work by Vaughn (1986) and McClelland (1974).

A second benefit is that the NWPCAM model projects stream impacts throughout the country, allowing both for highly aggregate weighted measures of water quality at the national and regional levels, as well as for more spatially refined results within regions.

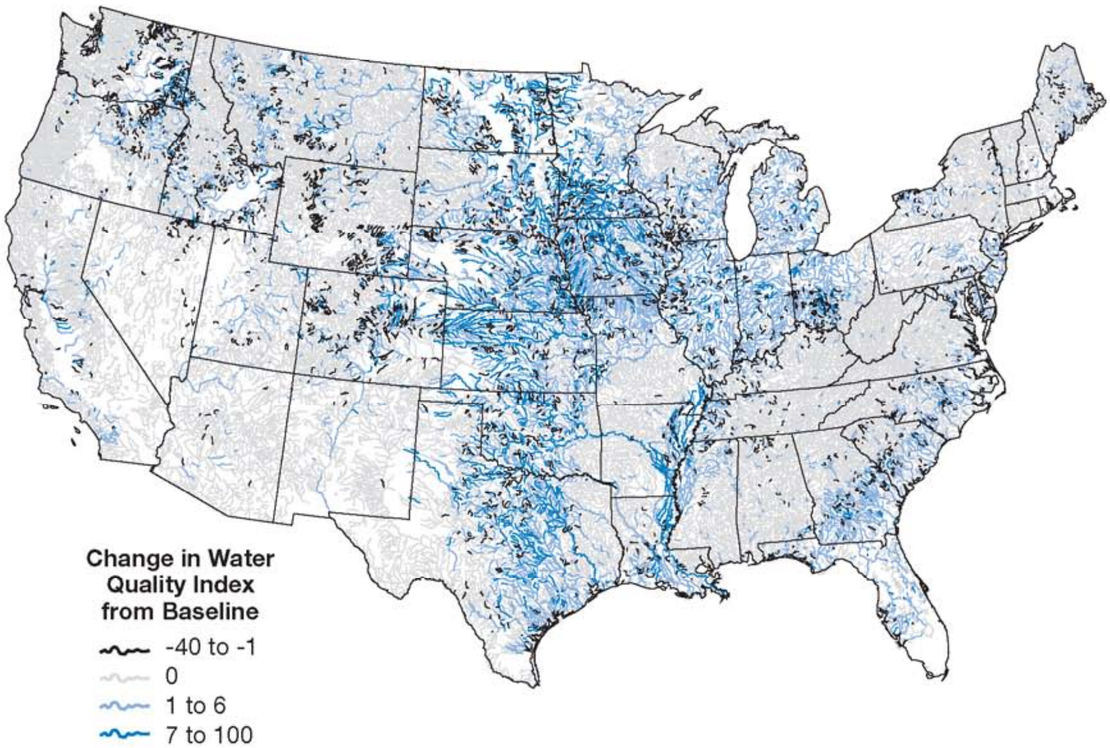
Results for the $6.80 CO_2 Eq. price scenario showed, among other things, that CO_2 makes up most of the net GHG mitigation, a decline of cropland production using conventional tillage, an expansion of conservation tillage, and an increase in afforestation of 5.8 million acres.

Figure 7-7 shows the water quality implications of the $6.80 per tonne CO_2 Eq. scenario distributed across the continental United States. The water quality changes reflect changes in loadings for all GHG mitigation activities, except for afforestation and livestock management. Note also that ASMGHG and NWPCAM are both static models, so the simulated water quality effects in Figure 7-7 are for a representative year (circa 2020, based on data inputs to the models used). Dark blue indicates substantial improvement in surface water quality, light blue presents small to moderate improvement, black spots indicate some water quality degradation, and grey areas reflect no appreciable change in water quality. For this relatively low GHG price, the aggregate, national-level surface WQI in NWPCAM increases by about 1.5 index points, which is a 2 percent improvement in the WQI from its baseline levels. Effects are primarily concentrated up and down the Mississippi River Valley and west of the 100th meridian.

Nitrogen loadings into the Gulf of Mexico are projected to decline by 144,000 tonnes per year under this price scenario. *This decline amounts to about half of the national goal under the Watershed Nutrient Task Force for solving the hypoxia problem* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001). These results are generally consistent with those shown in modeling of Gulf nitrogen loadings by Greenhalgh and Sauer (2003), although that study used different economic and biological models.

The changes vary across regions. Focusing on the Corn Belt and Southeast regions, as well as the nation as a whole, Table 7-2 shows the effects of the $6.80 per tonne CO_2 Eq. GHG price scenario for the ASMGHG-NWPCAM simulation. The national effects are consistent with the results for the FASOMGHG model described above, although total suspended solids increase nationally in the case study. Loadings decline in the Corn Belt region, because large areas of cropland are converted to conservation tillage. In contrast, loadings increase in the Southeast, mainly because there are adjustments in the types of crops grown. Despite this increase in loadings, the WQI for the Southeast improves very slightly. As noted above, the link between loadings and water quality outcomes depends on numerous location factors. Even within the Southeast, some regions experience lower loadings and water quality improvements.

Figure 7-7: Changes in Water Quality from Soil Carbon Sequestration and Other Agricultural Management Changes under \$6.8 per Tonne CO_2 Scenario in ca. 2020, using the ASMGHG-NWPCAM Integrated Agriculture Water Quality Model



Note: \$6.80/t CO_2 Eq. = \$25/ t C Eq., the modeled price.

Source: Pattanayak et al. (2005).

Table 7-2: Change in Pollutant Loadings for Selected Agricultural Pollutants and the WQI for the \$6.80 per tonne CO_2 Eq. Scenario, using the ASMGHG-NWPCAM Model Integration

	% Change in Pollutant Loading or WQI		
	Corn Belt	Southeast	National
Pollutant Loadings			
Nitrogen	–2.4	1.3	–3.1
Phosphorous	–0.7	0.3	–2.0
Total suspended solids	–2.4	0.2	0.5
Pesticides	–0.1	1.7	0.9
WQI	4.5	0.7	2.0

The improvements in these locations lead to aggregate gains in water quality at the regional level as loadings shift to areas that are less damaging to water quality.

The Pattanayak et al. ASMGHG-NWPCAM study suggests that, even for low GHG prices in the range of \$5 to \$15 per tonne CO_2, national-level water quality will improve. *At around \$5 per tonne of CO_2, this improvement could be around 2 to 3 percent for the nation and over 4 percent for the Corn Belt*, relative to baseline WQI measures.[1] The benefits occur heavily in the middle part of the country, as Figure 7-7 and Table 7-2 indicate, because the most intensive agricultural crop production currently occurs there.

Lastly, the reduction in nitrogen outputs specifically could benefit an emerging national water quality issue, hypoxia in the Gulf of Mexico.

Implications for Biodiversity of GHG Mitigation

Analysis of the impacts of GHG mitigation programs on biodiversity has gained substantial attention recently. Generally, increasing forest area restores habitat for plant, aviary, and soil organisms. It reduces forest fragmentation and connects protected-area and habitat fragments by providing corridors for seasonal or opportunist movement of broad-ranging species with large home range requirements (Wayburn et al. 2000; Franklin and Forman 1987; Mladenoff et al. 1997; Peters and Lovejoy 1992).

Huston and Marland (2003) and Gitay et al. (2002) suggest that there could be both positive and negative effects of terrestrial carbon sequestration programs on biodiversity, depending on the location. For instance, biofuel projects that remove natural forest cover and replace it with monocultural vegetation could reduce biodiversity locally. Alternatively, restoring bottomland hardwoods on agricultural lands in the southeastern United States would return that part of the landscape closer to its presettlement ecosystem and could thereby increase biodiversity on a local and regional scale. Huston and Marland (2003) and Gitay et al. (2002), however, do not attempt to quantify biodiversity impacts and mostly consider local effects.

Assessing the net effects of GHG mitigation on biodiversity is complicated. Plantinga and Wu (2003) explore carbon management through afforestation in Wisconsin and find that a scenario that increases forest area by 25 percent would cost \$100 to \$132 million to accomplish. Their findings also indicate that this scenario would provide additional consumptive and nonconsumptive wildlife benefits of \$61 million. Their study, however, assumed that the new forests would be similar to existing forests (i.e., landowners would not adjust the species types to maximize carbon payments) and that the forests would be managed in the same fashion that forests are currently managed. This result contrasts with other studies that argue that carbon sequestration payments could lead to suboptimal biodiversity outcomes (Caparros and Jacquemont 2003).

Clearly, GHG mitigation activities can influence biodiversity in positive and negative ways. The remainder of this section focuses on results from the FASOMGHG model scenarios that can provide some insight into these potential impacts.

Several forest-sector trends in the FASOMGHG results have potential implications for biodiversity. One trend is that the GHG price scenarios imply that more intensive management is aimed at increasing the growing stock of timber and carbon. Increasing the area of plantations is one such intensification. Tree planting now occurs on more than 2 million acres per year in the United States (Haynes 2003), and planted pine occupies just over 30 million acres of the land base (almost one-fifth of the U.S. South's timberland base). In the future, the area of planted pine is expected to rise by a factor of two-thirds by 2040, without considering

[1] Regional WQI measures in NWPCAM are aggregated weighted averages of the WQI for each stream reach in the region, weighted by the mile frontage of each reach.

GHG prices (USDA Forest Service 2002). With GHG pricing incentives, the area is projected to expand even more.

If the additional plantations resulting from GHG mitigation are planted on marginal or abandoned agricultural land, these plantations likely will improve biodiversity relative to current conditions. If, instead, the plantations are substituted for natural stands and managed in strict even-aged rotations, these plantations could reduce biodiversity relative to the natural stands they replace, as argued by Huston and Marland (2003). Some afforestation of marginal cropland in the Mississippi Alluvial Valley, however, uses a mix of native bottomland hardwood species to enhance biodiversity and restoration of native ecosystems (e.g., Schlamadinger [2003]).

The overall area of timberland is expected to increase under the GHG scenarios, suggesting that new lands planted to trees will be planted on lands that are currently agricultural. Conversion of intensively cultivated agricultural lands to forest cover, even a monocultural forest cover, is likely to have positive—or at least nonadverse—effects on biodiversity.[2] Forest edge effects and the juxtaposition of different habitats, and corridors for species movement are enhanced (Wayburn et al. 2000; Peters and Lovejoy 1992).

Thus, it is likely that the new forests projected by FASOMGHG will improve biodiversity relative to maintaining agriculture. In addition, the FASOMGHG model projects that forests will be managed in longer rotations when GHG price incentives are introduced. Longer rotations imply less-intensive harvesting regimes (and less forest and soil disturbance) and likely improved biodiversity. It is difficult to know with certainty which of these effects will dominate—intensive monoculture or expanding timberland area combined with less-intensive management on some land. The results of the scenarios explored in this report raise questions, however, which should be addressed in further research.

In addition to the forestry-biodiversity interaction, other changes suggested by the results in this report have biodiversity implications. As GHG prices rise above \$15 per tonne CO_2, the results in this report suggest that biomass energy becomes a competitive option for mitigation, and the area of land devoted to producing biomass crops expands. Huston and Marland (2003) state several concerns about the implications of using land for biomass production and potential reductions in biodiversity if this land involves removing natural timberland cover, wetlands, or other natural areas. If land devoted to biomass energy production involves converting cropland to biomass, however, biodiversity could increase.

Thus, the impacts of growth in biomass energy production on biodiversity will depend on which lands are converted for use. Given the aggregate nature of the FASOMGHG model, it is difficult to determine exactly what parcels of land will be converted to biomass production, so this report does not attempt to quantify these potential impacts. However, biodiversity issues related to biomass will become more important as carbon prices rise, given the potential penetration of biomass energy at the higher levels.

A final consideration relates to agricultural production. The results in the model imply substantial conversion to conservation and zero tillage, particularly at the lower GHG prices. Conservation tillage improves the health and diversity of the soil ecosystem (Lal et al. 1998) and would be expected to improve soil quality indicators substantially at the lower carbon prices. However, conservation tillage often also involves increasing inputs, such as chemical fertilizers and pesticides, which could offset some of the environmental gains from conservation tillage.

[2] Conversion of native grasslands to tree plantations, however, could diminish unique prairie ecosystems (Gitay et al. 2002), but this type of conversion is not expected to occur under the mitigation strategies analyzed in this report.

CHAPTER 8

Summary of Insights on Key GHG Mitigation Issues

This chapter concludes the report by showing how the results of the analyses presented in the previous chapters may have relevance for key issues regarding GHG mitigation from the forest and agriculture sectors.

Key Issues

Some key issues for GHG mitigation in forestry and agriculture are described below.

Level of Mitigation Achieved. *How much GHG mitigation is sought from the forest and agriculture sectors?* This report evaluates forestry and agriculture's potential to sequester carbon and reduce GHG emissions under different scenarios. As higher levels of mitigation are achieved, the portfolio of activities expands, as does the cost of mitigation.

Time Frame. *When would the mitigation occur?* This is a particularly critical question for carbon sequestration activities, which have complex time dynamics. Sequestration can generate substantial mitigation in the near to middle term (1 to 3 decades) but can decline after that because of biophysical saturation and practice reversal. Some alternatives such as biofuels have great technological potential to mitigate GHGs immediately and over the long term, but the infrastructure to handle widespread adoption could take decades to develop.

Comprehensiveness of Scope. Analytical results show that nearly 2,000 Tg CO_2 Eq. (or 2 billion tonnes) per year of mitigation potential exists at the highest-price scenario evaluated ($50/tonne CO_2 Eq.) if all private land, activities, and GHGs are included. However, this rather large mitigation potential can be reduced via criteria that narrow the activities, GHGs, and time frames considered.

- *Which activities and GHGs are included?* Inclusion could range from essentially all activities in forestry and agriculture that have some measurable GHG impact to a select few activities or GHGs that are targeted for their cost-effectiveness, desirable co-effects, or ease of monitoring.
- *What land base is included?* The analysis in this report has examined the mitigation potential from all private lands in the conterminous United States. But the scope could in principle be larger or smaller than that. For instance, public land can be managed to sequester carbon and otherwise mitigate GHGs, but these actions would presumably need to operate outside the type of economic incentive-based system evaluated in this report. Furthermore, programs may focus on specific regions or states either for economic or jurisdictional reasons.

Incentive Structure. The incentive structure refers to the form that the GHG mitigation incentives take and the appropriate incentive level for a given mitigation quantity. Related questions include the following:

- *What are the units of exchange?* For land-based actions, a critical question is whether payments are based on a per-tonne of CO_2 Eq. or per-acre basis. Although the latter is less costly to measure, monitor, and verify (MMV), the former tends to be much more efficient.

- *What mechanisms can be used to induce mitigation actions?* In a purely market-based system, mitigation incentives are determined by the laws of supply and demand. In a government-sponsored incentive program, compensation levels may be administratively determined.

Accounting Requirements. *How will GHG mitigation performance be measured?* Related questions include the following:

- *Are GHG mitigation quantities measured at a specific point in time, an average over some time period, or cumulatively since the beginning of the program?* The amount attributed to an action can be substantially affected by the completeness of the accounting over time.
- *Will adjustments be made to revise project-level mitigation totals?* Ideally, project quantification should reflect net mitigation over time. This suggests that adjustments may be necessary to capture baseline emission or sequestration levels that would have occurred without the project, GHG effects induced outside the project boundaries (leakage), and future carbon reversal likely to occur after a project ends.
- *Will non-GHG co-effects be included in mitigation evaluations?* The report has shown that mitigation actions may produce environmental co-effects that could influence the desirability of GHG mitigation strategies. If possible, should these co-effects be quantified and thereby modify the attractiveness of certain mitigation options?

Infrastructure. *What infrastructure or technical assistance might be helpful or necessary for landowners to realize potential mitigation opportunities?* Standardized and widely available measurement, monitoring, and verification guidelines and methods, for example, may help landowners overcome implementation barriers and engage in mitigation activities.

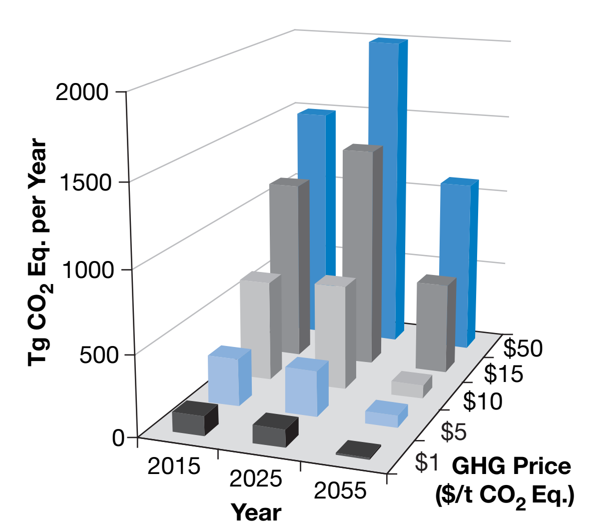
Insights from Analyzed Results

With these fundamental issues in mind, the results of the analyses throughout this report are used to provide insights that could shed light on the potential role of forestry and agriculture in GHG mitigation. These insights are enumerated and discussed below.

While national mitigation rates decline over time (under constant price scenarios), cumulative GHG mitigation steadily increases.

Total national mitigation—under the scenario with a constant GHG price of \$15/t CO_2 Eq. (\$55/t C Eq.)—is estimated to average almost 630 Tg CO_2/yr (172 Tg C) in the first decade, 655 Tg CO_2/yr (179 Tg C) by 2025, and decline to 86 Tg CO_2/yr (23 Tg C) by 2055 (see Figure 8-1). The total range of constant price scenarios evaluated is \$1 to \$50/t CO_2 Eq. (\$3.7 to \$184/t C Eq.). A declining rate of *annual* mitigation (i.e., occurring in a given year) over time is the result of saturating carbon sequestration (to a new equilibrium) in forestry and agriculture and carbon losses after timber harvesting.

Figure 8 1: National GHG Mitigation at Three Focus Dates by GHG Price: Average Annual



Cumulative GHG mitigation (i.e., achieved in the years up to a given year) for the $15/t CO_2 Eq. and other constant price scenarios steadily increases (see Figure 8-2). This cumulative amount reaches about 26,000 Tg CO_2 (7,080 Tg C) by 2055. On an *annualized* basis over 100 years, the $15/t CO_2 Eq. scenario generates 667 Tg CO_2/yr (182 Tg C) in GHG mitigation relative to the projected baseline. Annualized results represent the net annualized equivalent, or "annuity value," of all GHG mitigation over the entire 100-year period of analysis, using a discount rate of 4 percent.

Identifying attractive activities may require looking at a range of characteristics for each option.

Each potential mitigation activity has a wide range of characteristics that may make it more or less desirable. Table 8-1 highlights some of the key characteristics of each mitigation activity considered in this report: mitigation potential, regionality, non-GHG co-effects, and reversal risk. Reversal risk is particularly important if the action is expected to be short-lived and liability provisions are not in place to ensure that post-program reversal is addressed. Other potentially important considerations not included in this table (and not explicitly modeled in this report) include issues such as the difficulty of measuring, monitoring, and verifying project-level GHG effects and setting project baselines.

The quantity and timing of mitigation can determine the selected activities.

Table 8-2 shows that modest mitigation quantities (less than 300 Tg CO_2 Eq. per year) may be achieved in the near term, with activities that primarily include agricultural soil carbon and forest management, at less than $5/t CO_2 Eq. More ambitious levels require a different range of activities (e.g., afforestation and biofuels) and require $15 to 30/t CO_2 Eq. and above. Long-term mitigation requires permanent reductions in CO_2 and non-CO_2 emissions from agricultural practices (achievable at a relatively low GHG price incentive) and biofuel production. Biofuels are economically achievable only at the higher GHG prices and in the longer run, primarily because of capacity constraints on biofuel use in the short run.

Achieving a specific mitigation level within a narrow time frame may shift emissions to periods before and after the period of interest.

The report examines scenarios in which an average annual mitigation quantity is set for Year 2025 (the midpoint of the decade 2020 to 2030), which is

Figure 8 2: Cumulative GHG Mitigation in Tg CO_2 Eq.

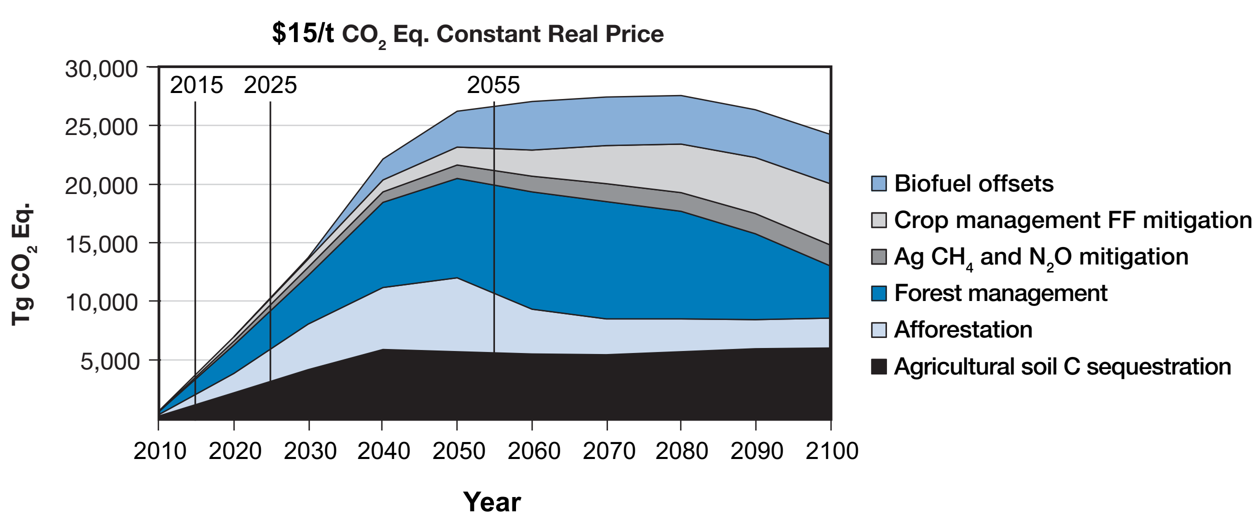


Table 8-1: Characteristics of GHG Mitigation Activities

Activity	GHG Mitigation Potential[a]	Regions of Emphasis	Key Environmental Co-effects	Reversal Risk[b]
Afforestation	High	South-Central and Corn Belt	Increases forest cover; improves water quality; biodiversity effects either (+) or (-) depending on characteristics of new forests and ecosystem displaced by new forests.	High
Forest management	Moderate	South-Central Southeast	Enhances forest biological stock; longer rotations can provide critical habitat.	High
Agricultural soil carbon sequestration	Moderate-low	Corn Belt Lake States Great Plains	Reduced erosion and nutrient runoff. Small increase in pesticide use.	Moderate-high
Fossil fuel mitigation from crop production	Low	South-Central and Southwest	Negligible effects within forest and agriculture sectors.	Low
Agricultural CH_4 and N_2O mitigation	Low	Corn Belt	Air quality improvements from some activities (e.g., manure management).	Low
Biofuel offsets	Very high	Eastern regions	Biodiversity effects depend on previous land use	Low

[a] Mitigation potential refers to mitigation attained at the highest GHG prices evaluated in report scenarios.

[b] Individual activities or projects could have lower or higher reversal risk, depending on activity and site characteristics.

Table 8-2: Potential Implications of Mitigation Level and Time Frame

Mitigation Quantity (Tg CO_2 Eq./year, annualized, 2010–2100)	GHG Scenario ($/t CO_2 Eq.)	Primary Near-Term Strategies (By 2025)	Primary Long-Term Strategies (Beyond 2025)
Low (<300)	$1–$5	Agricultural soil carbon sequestration	Forest management
		Forest management	Emissions reduction (CO_2 and non-CO_2) from agricultural activities
Medium (~300–1,400)	$5–$30	Afforestation	Forest management
		Forest management	Biofuels
High (1,400+)	$30+	Afforestation	Biofuels
		Forest management	Fossil fuel CO_2 and non-CO_2 emission reduction options

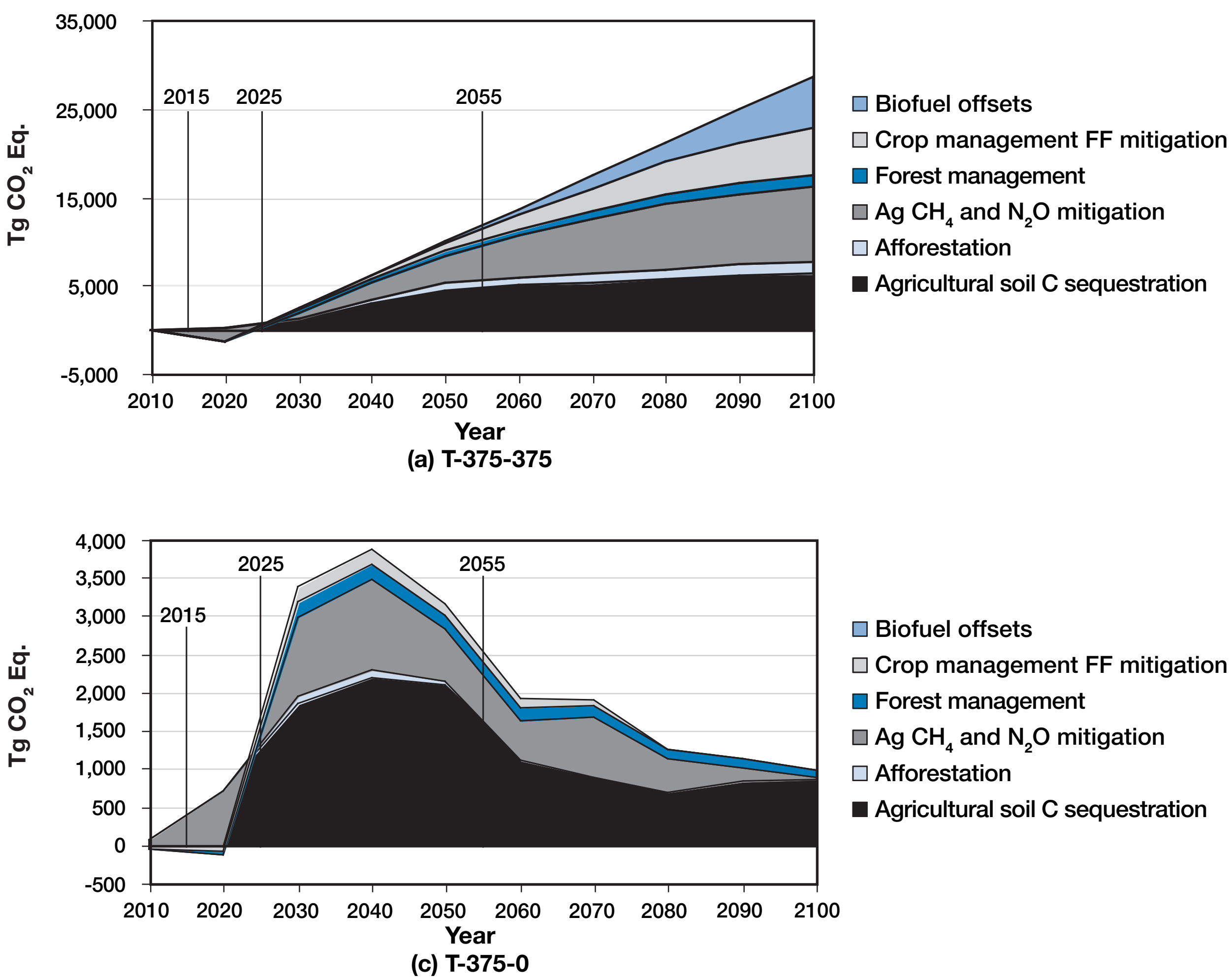
then either maintained, increased, or dropped after that period. Figure 8-3 (reproduced from Figure 5-2) shows the results over time as the fixed mitigation quantities vary.

The first unintended consequence is that the absence of any fixed level for the first decade (2010 to 2020) means that GHG emissions could exceed baseline levels, as producers substitute current (unconstrained) emissions for future (constrained) emissions. This is a form of temporal leakage and is reflected in the initial negative values in Figure 8-3 and occurs under all variations of the scenario.

This situation ultimately reverses when the 2025 mitigation quantity is met. However, another negative consequence occurs when the initial 2025 level is dropped thereafter (the second scenario in Figure 8-3), which leads to a large reversal of the carbon sequestered in the previous decades.

These negative consequences might be avoided if a cumulative mitigation quantity from a base year (e.g., 2010) onward is put in place instead of an annual quantity for the future time period and if the quantity is not dropped in the future.

Figure 8 3: Responses to Set Mitigation Quantities: Cumulative Mitigation to 2100
Quantities are Tg CO_2 Eq. cumulative net emissions reduction below baseline.
Note: Scale varies for each graph, from 4,000 to 35,000 Tg CO_2.



Under scenarios of rising GHG payments, forest and agriculture mitigation action may be delayed.

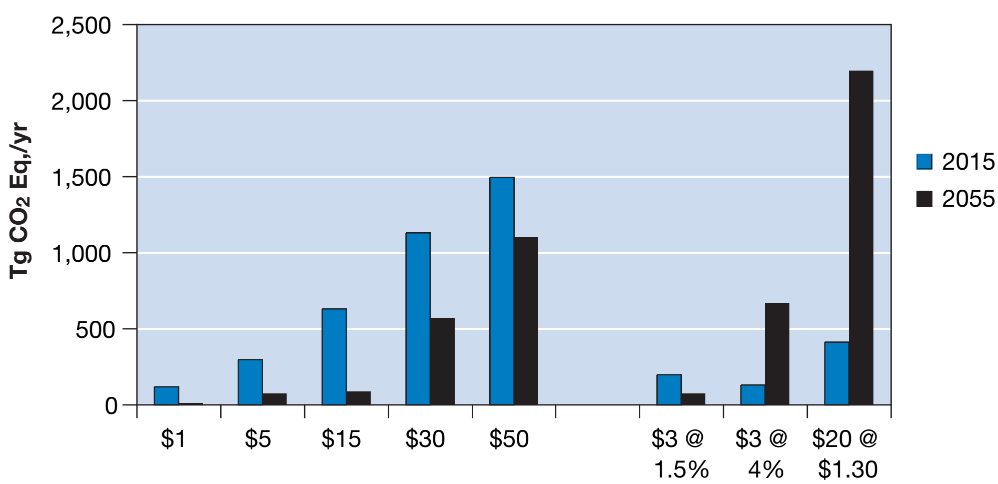
Scenarios simulating a rising GHG price show an increasing rate of GHG mitigation over the first few decades. However, the constant price scenarios show a declining rate of GHG mitigation over the same time period. Three rising GHG price scenarios are evaluated: \$3/t CO_2 Eq. rising at 1.5 percent and 4 percent/yr, respectively, and \$20/t CO_2 Eq. rising at \$1.30/yr. The analyses in Chapter 4 found that, compared to constant-price scenarios, rising prices can lead to delayed action (see Figure 8-4, reproduced from Figure 4-14 from Chapter 4).

The left side of Figure 8-4 shows the constant price scenarios at different levels, and the right side of the figure shows three rising-price scenarios. Rising prices generally cause delayed mitigation. The effect is most pronounced for the two scenarios with the higher rates of future price change. The primary reason for the delay is the "one-shot" nature of carbon sequestration activities. Under rising prices, if mitigation activities occur too early, more carbon will be sequestered at low prices in the near term and less carbon at high prices in the future. The economically optimal response, which the FASOMGHG model generates by assuming that landowners correctly know that prices will rise at the given rate, is to delay sequestration actions to take advantage of higher future prices.

GHG incentives reduce net emissions from the forest and agriculture sectors below baseline levels. If the incentives are strong enough, the joint sectors could move from a net emissions source to a sink.

The FASOMGHG baseline GHG projection for the combined forest and agriculture sectors shows a cumulative net *source* of emissions over time.[1] The mitigation scenarios (see Figure 8-5), however, generate responses that either reduce the size of the joint sector emissions source (at low GHG prices) or even produce a net GHG sink (at high GHG prices).

Figure 8 4: Constant Price Scenarios vs. Rising Price Scenarios and GHG Mitigation
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline for 2015 and 2055.



[1] EPA's U.S. GHG inventory shows these combined sectors to be a net sink currently; however, the EPA inventory includes carbon sequestration on public forest lands (an additional carbon sink), and FASOMGHG does not, thereby tipping the sectors' baseline GHG balance to a net source in the model.

Leakage potential from limiting included mitigation activities may be largely confined to the forest sector.

Model results in this report and in related research show that leakage potential within the forest sector can be moderate to high, depending on the activity and region (see Chapter 6). If all GHG mitigation activities in forestry and agriculture are included in a comprehensive approach scenario, leakage is negligible. Market effects elsewhere in the United States are captured in the mitigation totals computed by FASOMGHG.

However, if some forest activities and regions are singled out for mitigation, some of the benefits could be offset by emissions from other activities and regions (see Table 8-3). The primary driver of this leakage is the interaction between how much land is devoted to forests, called the extensive margin of forestry, and the intensity with which forests are managed, called the intensive margin. If only afforestation is included as a mitigation activity, but not the management of existing forests, the latter could suffer at the expense of the former, leading to carbon losses from the decline

Figure 8 5: Cumulative Net Emissions/Sinks for Forestry and Agriculture: Comparison of Baseline and Comprehensive Mitigation Scenarios at Constant Prices over Time

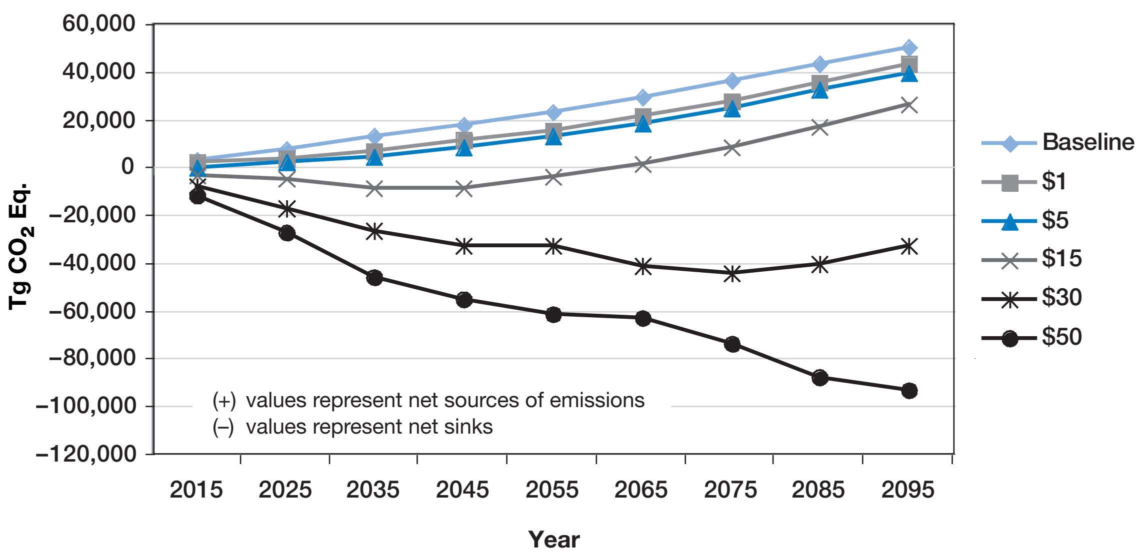


Table 8-3: Leakage Estimates by Mitigation Activity at a GHG Price of $15/t CO_2 Eq.
All quantities are on an annualized basis for the time period 2010–2100.

Selected Mitigation Activities	National Average Leakage Rate (%)
Afforestation only	24.0
Afforestation + forest management	–2.8
Biofuels	0.2
Agricultural management	–0.1
Agricultural soil carbon	5.7

Note: Negative sign indicates beneficial leakage (i.e., the selected activity increases mitigation in the nonselected activities).

in management. However, if both afforestation and forest management are given incentives, the results suggest that this leakage incentive essentially disappears (see Table 8-3).

The agricultural activities evaluated in this report do not appear to be as prone to leakage as forestry activities. Leakage estimates from the agricultural options were found to be less than 6 percent of the direct mitigation benefits. The reason for more limited leakage effects in agriculture is that the changes in agricultural practices do not have as profound an impact on agricultural commodity markets as the forest activities do on timber markets.

Raising GHG mitigation levels in forestry and agriculture can cause environmental co-effects, both good and bad.

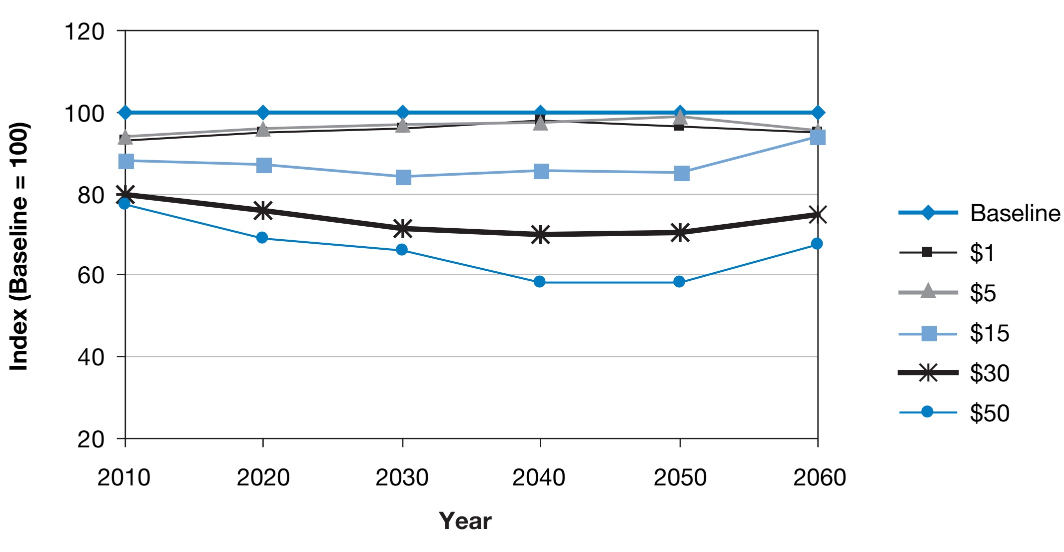
Large changes in land use and production can also have a substantial impact on non-GHG environmental outcomes in forestry and agriculture, primarily because of the role of agricultural soil carbon sequestration in the mitigation portfolio at a fairly low GHG price scenario (e.g., $5/tonne CO_2 Eq.). Even such a low GHG price can induce changes in tillage practices across many cropland acres. These practice changes also reduce erosion and nutrient runoff to waterways as a co-benefit but can lead to a modest increase in pesticide use as a co-cost (Figure 8-6). Other potential environmental effects, such as biodiversity issues, are not modeled in this report but are addressed in Chapter 7.

Taking these environmental co-effects into consideration could affect the relative attractiveness of competing mitigation options. In general, a modest GHG mitigation action will probably have negligible effects on non-GHG outcomes within the sectors. However, the more aggressive the mitigation action, the more likely that co-effects may factor into the net benefits of GHG mitigation.

Payment method will determine efficiency of mitigation activities.

Paying on a per-tonne CO_2 Eq. basis is more efficient than paying on a per-acre basis to generate additional GHG mitigation. Compared to the scenario paying for afforestation only (at $15/t CO_2 Eq.), paying for afforestation on a uniform $100 per-acre basis generates only 30 percent as much additional carbon but requires 60 percent as much in payments. Per-acre payments do not directly vary with the biophysical potential of the site. The inefficiency could be remedied somewhat by adjusting per-acre payments based on land productivity.

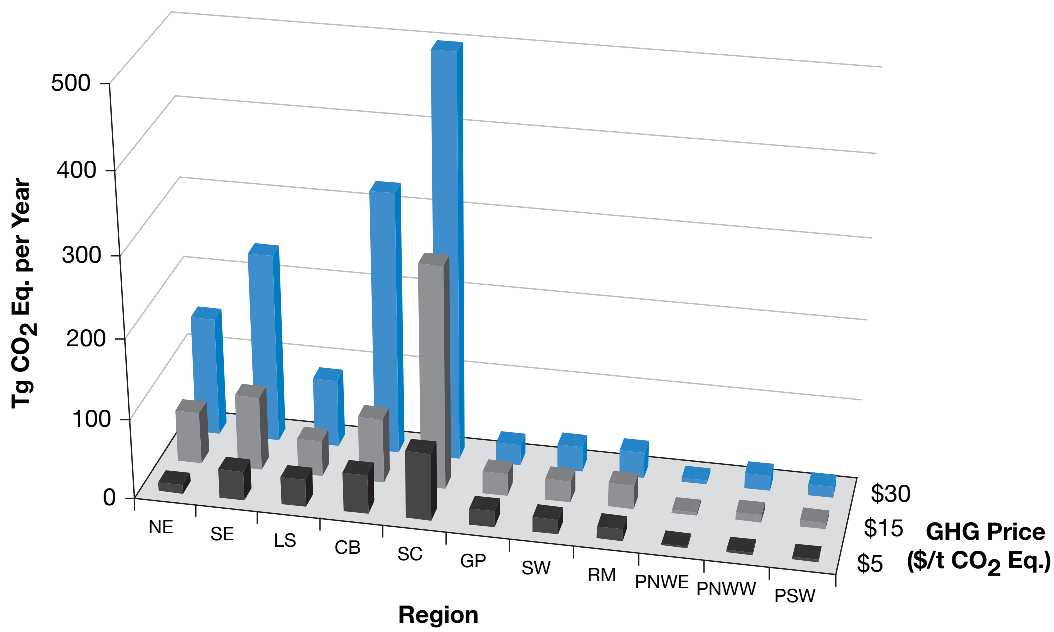
Figure 8 6: Nitrogen Runoff Index over Time by (Constant) GHG Price Scenario



If outreach is needed to deliver GHG mitigation, these efforts might focus in regions with the largest mitigation potential.

As shown in Figure 8-7 (reproduced from Figure 4-11), the regional distribution of mitigation opportunities is skewed toward the eastern United States. Federal and other public lands are not included in this analysis, thereby ignoring mitigation potential on those lands. However, public lands management, if included, would clearly elevate the role of the western United States in a national strategy. On the remaining private lands, however, the regional distribution does vary some with the level of mitigation sought. At low levels of mitigation and prices, the two South regions (South-Central and Southeast), via forest management, and two Midwest regions (Corn Belt and Lake States), via agricultural soil carbon sequestration, are the focal regions and activities. As prices rise and mitigation levels expand, farmers in the South and Midwest may participate by planting trees on agricultural land. If GHG incentives are strong enough to induce biofuel production, landowner participation could expand beyond the Midwest and South to include the Northeast region.

Figure 8 7: Total Forest and Agriculture GHG Mitigation by Region
Quantities are Tg CO_2 Eq. per year net emissions reduction below baseline, annualized over the time period 2010 2110.



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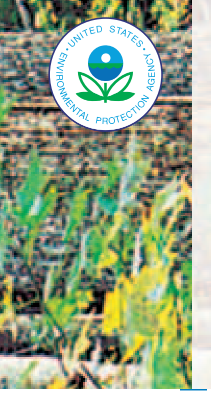

Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture

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